



Investigation of Pellet Acceleration by an Arc Heated Gas Gun

Andersen, S.A.; Bækmark, L.; Jensen, Vagn Orla; Michelsen, Poul; Weisberg, Knud-Vilhelm

Publication date:
1988

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):
Andersen, S. A., Bækmark, L., Jensen, V. O., Michelsen, P., & Weisberg, K-V. (1988). *Investigation of Pellet Acceleration by an Arc Heated Gas Gun*. Risø-M No. 2744

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.



Investigation of Pellet Acceleration by an Arc Heated Gas Gun

**S.A. Andersen, L. Bækmark, V.O. Jensen, P. Michelsen, and K.V.
Weisberg**

INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN*

S.A.Andersen, L.Bækmark, V.O.Jensen. P.Michelsen, and
K.V.Weisberg.

Abstract. This report describes work on pellet acceleration by means of an arc heated gas gun. Preliminary results were described in Risø-M-2536 and in Risø-M-2650. This final report describes the work carried out from 1987.03.31 to 1988.09.30. An arc-heated hydrogen gas source, for pneumatic acceleration of deuterium pellets to velocities above 2 km/s, was developed. Experiments were performed with an arc chamber to which different methods of hydrogen supply were possible, and to which the input of electrical power could be programmed. Results in terms of pressure transients and acceleration curves are presented. Maximum pellet velocities approaching 2 km/s were obtained. This limit is discussed in relation to the presented data. Finally this report contains a summary and a conclusion for the entire project.

* This work was done under Art.-14 contract No.JR4/9006
Extension No 1 between the JET Joint Undertaking and the
Fusion Research Unit of the Association Euratom-Risø National
Laboratory.

October 1988

Risø National Laboratory, DK-4000 Roskilde, Denmark

ISBN 87-550-1460-7

ISSN 0418-6435

Grafisk Service, Risø 1988

CONTENTS

I. INTRODUCTION	5
II. EXPERIMENTAL SET-UP	6
III. ACCELERATION OF PELLETS WITH PELLET FED ARC CHAMBER ...	7
Acceleration of foam pellets	7
Acceleration of deuterium pellets	8
Experimental procedure	9
Results	10
IV. ACCELERATION OF DEUTERIUM PELLETS WITH GAS FED ARC	
CHAMBER	11
Experimental set-up	11
Experiments with 150 bar valve pressure	12
Experiments with full 300 bar valve supply	12
Results	13
V. GAS INJECTION IN CLOSED ARC CHAMBER	14
Arc heating efficiency and pressure increase by	
gas injection in closed arc chamber	14
Measurement of pressure transient in gas	
injected arc chamber	15
Control measurements of feed pellets	16
Pressure build-up in closed chamber. Slow pellet	
injection	17
Pressure build-up in closed chamber with fast pellet	
injection	18
VI. SUMMARY AND CONCLUSION	20
ACKNOWLEDGEMENTS	22
REFERENCES	23
FIGURES	24

INTRODUCTION

This report describes work done under an Art.-14 contract No.JR4/9006 Extension No 1 between the JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory. The report, which is the final one, covers the work done in the period from April 1987 to the end of September 1988 and contains also a discussion of the whole work which was initiated in July 1984. Preliminary results have been described in the reports /1/, which covers the first part of the contract from the start of June 1984 to the end of August 1985, and in /2/, which covers the period September 1985 to March 1987.

Report /1/ describes the background of the work, the experimental set-up in details and the preliminary results obtained from acceleration of deuterium pellets. Most of the work described in /1/ concerned the establishment of the experimental set-up with test of the cryogenic pellet producing unit and the diagnostic equipment. In these tests deuterium pellets were fired by an ordinary fast valve, room temperature hydrogen propellant gas acceleration and only a few preliminary results were obtained with arc acceleration.

Report /2/ describes the results obtained in the continued work with acceleration of extruded deuterium pellets by means of a cryogenic arc chamber. A new concept of a hydrogen pellet fed, room temperature arc chamber was tested and used for acceleration of polyurethane pellets. The work with development of a pipe gun for production of large feed pellets for the pellet fed arc chamber was also described and so was the design considerations for a high pressure arc chamber for pellet and high pressure hydrogen gas feeding.

The present report describes the work with pellet acceleration using a high pressure arc chamber. The experimental set-up is discussed in chapter 2. In chapter 3 the work with acceleration of deuterium pellets with gas fed arc chamber is described. In chapter 4 acceleration with pellet fed arc chamber is described and in chapter 5 a discussion on measurements of pressure increase with pellet feeding and gas feeding, respectively, can be

found. Finally a summary and a discussion of the whole work can be found in chapter 6.

II. EXPERIMENTAL SET-UP

The experimental set-up used for the measurements in this report, which is not much different from the set-up used in /2/, is shown in a schematic form in Fig.II.1. This figure will be used to discuss the different part of the hardware. The whole set-up can be divided into four main parts: The arc chamber, the pellet chamber (cryostat), the gun barrel with diagnostic and the power supply for the arc chamber. All the experiments presented in this report were performed with the high pressure proto-type arc chamber described in details in chapter V of /2/. In the case of acceleration of plastic pellets, the pellet was charged into the gun barrel itself by a modified valve. In the case of acceleration of deuterium pellets, the pellets was produced in the freezing cell of the cryostat delivered by CENG /3/. As seen from the figure the diagnostic consisted of pressure transducers, optical detectors to measure pellet speeds and a flash photo camera. Besides this, measurements were performed of arc voltage and arc current and between pellet shots various temperature measurements in the cryogenic system. The JET designed power supply mentioned in /1/ was used in most cases for the arc current. The magnetic coil surrounding the arc chamber could be either connected in series with the arc or supplied from a Risø designed power supply. The main principle of the JET power supply and the diagram of the connection to the arc chamber is shown in Fig.II.2. The filter installed parallel to the arc was necessary in order to reduce high frequency oscillations which caused false triggering of the crowbar and of other instruments. In order to ensure a reproducible ignition, an additional ignition electrode was used. This electrode, consisting of a 0.8 mm tantalum wire, was introduced axially through the centre electrode, insulated by means of a 2 mm outer diameter alumina tube. The alumina tube ends at the tip of the graphite electrode and the tantalum wire extrudes about 2 mm from the tube end into the arc chamber cavity. Outside the chamber the tantalum wire is connected through 25 Ω to ground. In this way a

current limited pre-discharge can be ignited in the small gap (about 1 mm) between the tantalum wire and the graphite electrode at high initial pressures and for pressures up to about 5 bar this pre-discharge switches the main discharge in less than a hundred microseconds. This time lag decreased with decreasing initial pressure. Also with pellet injection it was generally less than 100 μ s.

III. ACCELERATION OF PELLETS WITH PELLET FED ARC CHAMBER

Acceleration of foam pellets

For the experiments described in this section the arc chamber was mounted with a gun barrel of length 1060 mm and 3.2 mm inner diameter, equipped with 5 optical detectors and 3 or 5 piezo-ceramic discs for time of flight measurements, and 3 PCB pressure transducers (model 105A22) for pressure measurements.

Experiments were performed with pellets of polyurethane foam and of styrophor foam. The pellets were charged into the gun barrel by a charge mechanism made from a modified Nupro-valve. The distance from the arc chamber to the charge mechanism is 86 mm. The arc chamber is fed with hydrogen feed pellets (5.5 mm^3 and $200 \text{ bar} \cdot \text{cm}^3$) from the feed pellet injector through a plastic tube. The velocity of the feed pellets is measured with two optical detectors placed on the pellet injection tube on the arc chamber. The signal from the last detector triggers via an adjustable delay unit the gate valve which is build into the discharge chamber. The gate valve closes the pellet injection channel when the pellet has arrived into the arc chamber. The arc is triggered by a signal from an impact transducer on the gate valve when it is in the closed position.

Experiments have been accomplished both with the magnetic coil in series with the discharge driven by the JET power supply and with the coil driven separately by the Rise power supply. Different electrode geometries were tried with a molybdenum electrode and a stainless steel nozzle with a tangential inlet channel for the feed pellets. The latter is to obtain a rotation of the feed pellet along the arc chamber cylinder wall.

These experiments were mainly used for testing the whole system, power supply, pipe gun, diagnostic, etc. The foam pellets, which were 3.2 mm in diameter, were investigated by static compressibility measurements, which showed that the polyurethane pellets start to collapse at about 50 bar as compared to about 100 bar for the styrophor pellets. However, the styrophor pellets were found to be destroyed much easier than the polystyrene pellets when exposed to the arc acceleration for unknown reasons. With the polystyrene pellets, velocities up to 2.2 km/s were obtained as can be seen from Fig.III.1. It can be noted that most of the acceleration takes place within the first 50 cm.

Acceleration of deuterium pellets

A cryostat developed by CENG and described in /3/ was installed in July 1987 in order to produce deuterium pellets. This cryostat was provided with a 1.0 m gun barrel of stainless steel with an inner diameter of 3.2 mm and an outer diameter of 4 mm. The arc chamber is fed with hydrogen feed pellets, 5.5 mm diameter and a total gas amount of $200 \text{ bar} \cdot \text{cm}^3$, and induced with a velocity of the order of 40 - 50 m/s. from the feed pellet injector through a plastic guiding tube. The CENG cryostat is controlled by a separate gas supply and temperature control unit and the feed pellet injector is controlled by a PLC (programmable logic controller) programmed to co-ordinate the two systems. As with the foam pellet experiment the feed pellet velocity is measured from the optical detectors placed around the guiding tube close to the inlet of the arc chamber, and the trigger signal for firing the arc is produced by the gate valve in its closed position. A molybdenum central electrode (positive polarity) and a ceramic nozzle with a special groove for guiding the feed pellets to the arc cavity were used.

For acceleration measurements along the gun barrel 8 piezo-electric discs mounted on the barrel were applied. The final velocity was measured with optical detectors placed in front of the gun barrel in positions 1459 and 1589 mm from the freezing cell. The pressure evolution in the arc chamber was measured with an acceleration compensated miniature quartz pressure transducer (PCB model M113A03, 1 kbar, 500 kHz). The discharge characteristic was registered by measuring the arc voltage and the arc

current. Figure III.2 shows the gas supply system in a schematic form.

Experimental procedure

Referring to Fig.III.2 of the gas supply diagram, the pellet production take place in the following way. With the valves V1, V3, V4, and V5 closed, deuterium gas for the CENG cryostat and hydrogen gas for the pellet feeding cryostat is supplied. The deuterium freezing cell is fed from both sides, partly through the gun barrel and partly through the discharge chamber with the manual valve V2 between the deuterium cryostat and the arc chamber open. (this valve is actually only closed when the arc chamber is serviced or changed). The hydrogen freezing cell is similarly fed from two sides. The pellet creation in the two systems is started simultaneously and is programmed to run a certain time for each system. After the completion of the longest creation time (hydrogen-pellet approximately 4 minutes) the valves V1, V3, and V4 are opened for pumping of the rest of the feed gas. Now the system is ready for shooting and the firing is activated with a short opening of the magnetic valve V5, which causes a hydrogen gas pressure of 200 - 800 mbar to accelerate the feed pellet through the valve V4 and the guiding tube to injection into the arc chamber. When the feed pellet passes through the optical detector O₂ a trigger signal for closing the gate valve is provided. When it is closed a shock detector submit a signal for triggering the electrical discharge. The discharge is established by a preprogrammed firing of the capacitor bank (120 capacitors) in the arc power supply, connected to the arc chamber as shown in Fig. II.2. When the first capacitor is discharged by triggering of the corresponding thyristor, the charge voltage (up to 750 V) multiplied with the ratio of the pulse transformer (4 times) is applied to the electrode of the arc chamber. The arc is ignited in two steps as described in chapter III: Firstly, a start discharge between the main centre electrode and a secondary electrode, consisting of a thin tantalum wire connected through a 25 ohm resistor, is ignited. Secondly, the ionisation from this start discharge causes ignition of the main arc burning between the main centre electrode and the arc chamber wall. The current in the secondary electrode is limited by the 25 ohms resistor. The current diagram Fig.II.2

shows the magnetic coil connected in series with the discharge, but experiments were also performed with the coil supplied from a separate power supply. The arc voltage is measured across a 800 ohm resistor shunted between the centre electrode and the return cable. The current transformers for voltage and current measurements provide a galvanic separation between the measuring system and the arc current system.

Results

Fig.III.3 and Fig.III.4 show data from shots with the arc current power supply programmed in two different ways. The coil (29 turns) is in this case in series with the arc. The hydrogen feed pellet, approximately $200 \text{ bar} \cdot \text{cm}^3$, is injected with a velocity of 45 m/s. The temporal distribution of the triggering of the capacitor bank is shown in Fig.III.5 and Fig.III.6. The difference in the firing system is reflected in the profile for the discharge current. Apart from this, the discharge characteristics are rather similar. In both shots an arc voltage of approximately 1 kV, a maximum arc current of 3.5 kA, a maximum pressure of 200 bar in the arc chamber, and a pellet velocity of $\approx 1900 \text{ m/s}$ are obtained. Plots of the piezo detector timing signals show in both cases a start acceleration of $\approx 5 \cdot 10^6 \text{ m/s}^2$ decreasing rapidly along the gun barrel. The velocity and acceleration plots are calculated from the arrival time to the first six piezo-electrical transducers along the gun barrel. The signals from the first four are shown in Fig.III.7. and Fig.III.8. The arrival time to PZ no.5 and 6 is obtained from a Vuko digital oscilloscope. The reproducibility of the discharge characteristic is, however, a problem in most cases. Fig.III.9 shows the current-voltage characteristic for two shots (no.28 and no.29) taken right after each other and with the same firing conditions. It is seen that the voltage in shot no.29 shows a suddenly jump during the progress of the discharge, which causes a higher maximum pressure and thereby a higher acceleration. The final pellet velocity for shot no.28 is 1590 m/s and for shot no. 29 it is 1800 m/s. This kind of variations from shot to shot with the same firing conditions is often seen and is probably caused by uncontrollable effects from the motion of the feed pellet and its breakdown in the arc chamber.

The main results from all the successful shots where the arc chamber is loaded with feed pellets are shown in the following figures. Fig.III.10 shows the pellet velocity as a function of the peak pressure. Fig.III.11 shows the peak pressure versus electrical peak power dissipated in the arc. These results together, i.e. pellet velocity versus power are shown in Fig.III.12. Finally, the arc power, the arc voltage, and the arc resistance as functions of arc current are shown in Fig.III.13 - Fig.III.15. All these measurement indicate the lack of reproducibility of the discharge.

IV. ACCELERATION OF DEUTERIUM PELLETS WITH GAS FED ARC CHAMBER

The purpose of these experiments were to study the acceleration of deuterium pellets by means of arc heated propellant gas produced by injection of high pressure hydrogen gas into the arc chamber. Before these experiments were performed the pressure increase in the arc chamber was studied. However, this investigation is described in details in Section V.

Experimental set-up

The 300-bar fast valve from CENG was connected to the 6 mm diameter inlet tube of the large prototype arc chamber (Fig.IV.1). The arc chamber was equipped with a graphite gas nozzle (instead of the pellet nozzle with guiding groove) and with a graphite central electrode and graphite lining on the cylindrical arc cavity wall. The arc was driven in series with the magnet coil by the JET power supply, and the HF-noise suppressing filter was applied. The outlet from the arc chamber was connected to the deuterium pellet forming unit (CENG-cryostat), which in the first experiments was equipped with the 3.2 mm diameter, 0.5 mm wall and 1 m long barrel to which 8 piezo electric ceramic discs were clamped for pellet timing measurements. The positions of the discs downstream from the deuterium-freezing cell were: 86.0, 130.5, 219.4, 319.6, 430.8, 559.5, 749.7, 970.1 mm and the positions of the two optical muzzle velocity detectors were: 1459 and 1589 mm. Furthermore the diagnostic included: a PCB pressure transducer for monitoring the arc chamber pressure and

a 20 ns flash photo equipment for pellet photos.

In the first experiments the compressor for high pressure charging of the fast valve was not used; hydrogen up to about 150 bar was taken directly from the pressure flask to the valve. Due to jitter (of the order of 100 μ s) in the opening function of the fast valve a fixed delay between the firing of the valve and triggering of the arc and the recording equipment, which was tried at first, could not be used. Instead of this, the arc was triggered on a fixed level (5-10 bar) of the rising edge of the signal from the pressure transducer in the arc chamber.

Experiments with 150 bar valve pressure

Data from a typical shot with 155 bar valve pressure are shown in Fig.IV.2. In the four time windows (1 ns sweep time) of Fig.IV.2 the arc characteristics together with the pressure transient in the arc chamber, with and without arc ignition, are shown. In this shot 20 capacitors were used in the following sequence: first 5 at 50 μ s interval, next 5 at 1 μ s interval, next groups of 1, 2, 3 and 4 at 25 μ s interval. The batteries were charged to 770 V and the pulse transformer set to a voltage step-up of 4. In Fig.IV.3 the arrival time, the deduced velocity, and acceleration as a function of distance from the starting position (the freezing cell) of the deuterium projectile pellet are shown. From this figure it is seen, that the pellet leaves the barrel (1 m) at about $t = 1$ ms, whereas acceleration only takes place in the first 500 mm, corresponding to about $t = 700$ μ s. At this time about 1 kJ has been dissipated by the arc. The velocity increase is from ca. 1300 m/s without arc ignition to ca. 1700 m/s with arc at the applied 155 bar valve pressure. This corresponds to an energy increase of approximately 5 J for a 9 mg pellet (length from photo around 6 mm). Thus the energy efficiency (increase in pellet energy/arc energy) is only about 0.5 %.

Experiments with full 300 bar valve supply

The experiments discussed above with hydrogen injection from the CENG fast valve into the arc chamber were continued after the installation of the compressor for obtaining the full 300 bar valve pressure. In these experiments the thin-walled barrel was

replaced by the 3.2/9.5 mm diameter barrel at which PCB (Model 105A33) transducers were mounted. During the past work with the CENG D₂-pellet forming cryostat in connection with the arc chamber, it was observed that the working temperature of the freezing cell had gradually increased from approximately 5.3 K (700 Ω) to approximately 5.6 K (660 Ω). When the cryostat was opened for the exchange of barrels, the cell was examined for the cause of this temperature change. It was found, that the inner diameter of the barrel piece connected to the cell had become smaller than 3.2 mm, probably due to a layer deposited by exhaust from the arc chamber. The barrel piece was honed to its original 3.2 mm and the working temperature was after that observed to decrease to a value close to the original. Initially the arc chamber was again equipped with all graphite electrodes (centre electrode, cavity wall, gas inlet nozzle) and glass ceramic (Macor) insulator. However, as the graphite nozzle was broken, probably by the increased blow from the full 300 bar valve pressure it was replaced by a nozzle piece made from molybdenum. Also the central graphite electrode was replaced by a molybdenum electrode. This was done in order to increase the life time of the alumina tube, which was used for insulating the auxiliary coaxial ignition electrode. It was observed that the alumina tube was more quickly eroded and destroyed near the arcing tip when used in connection with a central electrode made of graphite than with one made of molybdenum.

Results

Figure IV.4-7 show data from a shot with 300 bar filling pressure of hydrogen in the fast valve. The arc was driven in series with a 20 μ H inductance by 38 capacitors of the JET-power supply. The firing was programmed to produce a current profile with a peak intensity at the pulse end. The magnet coil was driven by the Risø-power supply charged to 2.7 kV producing a magnet current pulse with a peak current of 1.75 kA and a length of 800 μ s. This current pulse was delayed 300 μ s with respect to the arc current pulse. With no delay, the arc voltage was found to rise very quickly at the start of the pulse and the arc was extinguished (blown out) in an early stage of the inlet of gas from the 300 bar valve. In Fig. IV.4 the arc voltage, the arc current, the arc power and the arc energy are shown as functions

of time in four 1 ms time windows. Figure IV.5 shows the pressure transients in the arc chamber and at 3 positions along the barrel with and without the arc. Figure IV.6 shows a plot of the arrival time of the D₂ pellet as a function of distance from the freezing cell, of the velocity and acceleration as calculated from the arrival times, and the measured chamber pressure also plotted versus pellet position. This plot shows that the pressure peaks in the arc chamber at the time where the pellet has reached a position of about 700 mm from the freezing cell. Fig.IV.7 shows a shot similar to Fig.IV.6, but for a case with the fast valve connected directly to the barrel. The differences between these two shots are further discussed in chapter VI.

V. GAS INJECTION IN CLOSED ARC CHAMBER

The purpose of these experiments was to measure the arc heating efficiency from the pressure increase produced by the arc, and to investigate discharge characteristics in detail under various conditions. Measurements of pressure increase were performed partly with a stationary filled arc chamber partly with pellet feeding.

Arc heating efficiency and pressure increase by gas injection in closed arc chamber

In this experiment a modified Skinner valve (orifice 3.2 mm, 200 cm³) was connected to the propeller gas inlet tube of the large prototype arc chamber. The arc chamber was equipped with a 60 turn coil, graphite centre electrode, stumatite insulator and glass ceramic (Macor) nozzle. The arc cavity volume was 4 cm³. By means of a pulsed power supply the valve could be operated as to give a controlled amount of hydrogen gas into the arc chamber.

Figure V.1 shows results from a shot with an initial pressure of 40 bar in the valve. Back-streaming of gas from the arc chamber to the valve could happen, therefore, only results from shots with a final arc chamber pressure smaller than the valve reservoir pressure were used. The arc was driven in series with the coil by the JET-power supply. A total of 65 capacitors were

fired within 1 ms and programmed in order to produce a double humped current profile. It is seen from Fig.V.1 that the increase in chamber pressure with arc ignition is about 20 bar. In a total volume of about 5 cm³ (cavity + inlet line + barrel segment to closed valve) this corresponds to an increase in pressure energy of 100 bar·cm³ or 10 Joule. With a total of about 800 J electrical energy dissipated by the arc this corresponds to an efficiency of about only 1%. In estimating the heating efficiency it is assumed that the same amount of gas is introduced into the arc chamber with and without arc ignition, with unchanged valve parameters. However, even with no changes in valve operation parameters (valve pressure and valve power pulse) the gas flow conditions are not the same in the two cases. Due to the faster pressure build-up in the arc chamber with ignition, less gas will be introduced in this case than with no ignition. With no correction for this effect the estimated heating efficiency comes out too small. However with a maximum pressure produced in the arc chamber well below the valve pressure, this error is believed to be small. A more important objection to this experiment is, that information on heating efficiency at more relevant pressures (several hbar) is not produced. It is seen from Fig.V.1 that the arc voltage remains low.

One reason for the very low heating efficiency produced in this experiment as compared to earlier results from feed pellet injection could be that the electrode/nozzle combination used is not suited for gas injection. As mentioned above an insulating (Macor) nozzle element was used in this experiment. This means that the arc current must run from the centre electrode to the cylindrical wall electrode (graphite) such that the current path does not intersect the gas path. In later experiments with gas injection at higher pressure levels (with CENG 300 bar valve) a conducting nozzle element (graphite/molybdenum) is used. This is found to produce higher arc voltages.

Measurement of pressure transient in gas injected arc chamber

The purpose of these experiments were to test the arc/gas coupling efficiency in terms of arc voltage and electrical power input with a changed electrode geometry as compared to the mea-

surements described above. In this experiment the cylindrical wall of the arc chamber cavity was covered by an insulating Macor liner so that the arc was drawn from the molybdenum central electrode to the stainless steel nozzle. Hydrogen gas was injected from the modified Skinner valve with a filling pressure of 45 bar. During the measurements the valve was kept open and also an open barrel was used as outlet for the arc chamber.

Figures V.2-4 show results for the arc characteristics and the pressure transients in the arc chamber and at one position of the barrel (290 mm from the arc chamber) for three shots with an increasing number of capacitors used by the JET-power supply for driving the arc. It is seen that with this geometry a peak power of 1.5 MW is produced at the peak current of about 3 kA (Fig.V.4) as compared to about 0.8 MW in the earlier experiment (Fig.V.1), where the arc was drawn from the central electrode to a conducting cavity wall. It should be noticed that in present experiment the gas flows freely from an open valve through an open arc chamber during the measurement, whereas a closed arc chamber filled from a pulsed valve was used in the earlier experiment.

These results should be compared with the results obtained from the experiments with gas injection from the 300 bar valve (chapter IV). From Fig.IV.4 it is seen that with an arc current again of about 3 kA a power of 3-4 MW is produced at this higher pressure level.

Control measurements of feed pellets

In the experiments above (Sec.III) we tried to increase the size of the feed pellets in order to observe the effect on the arc behaviour and the pressure build-up in the arc chamber and the barrel. We found, however, that when more than about 200 bar·cm³ of hydrogen was condensed in the freezing cell of the feed pellet injector the pellets were broken when passing the optical detector, which controls the gate valve, and only low pressures were produced by the shots. In order to examine how much of the condensed hydrogen in the feed pellets actually entered the arc chamber, a measuring volume (120 l) with a Baratron pressure transducer was connected to the barrel outlet of the arc chamber.

It was found that feed pellets with a condensed amount of hydrogen of up to $280 \text{ bar}\cdot\text{cm}^3$ were collected almost completely (95%) in the arc chamber. When more than this amount of hydrogen was condensed in the pipe gun, the pellets could not be fired intact from the gun. The optical detector indicated broken pellets and by re-heating the freezing cell, remnant hydrogen was observed. For pellet sizes between 200 and $280 \text{ bar}\cdot\text{cm}^3$ the pellets were intact but often accompanied by small fragments, which were not present below $200 \text{ bar}\cdot\text{cm}^3$. As these fragments often caused incorrect triggering of the gate valve, the present feed pellet gun is useful only for feed pellets up to about $200 \text{ bar}\cdot\text{cm}^3$.

Pressure build-up in closed chamber with slow pellet injection

The purpose of these measurements was to study the pressure build-up in the arc chamber and in the barrel at initial projectile pellet position as a function of feed pellet size.

In this experiment the large prototype arc chamber was fitted with a piece of 3.2 mm diameter barrel, which was closed at the end with a pressure transducer of which the membrane was facing the arc chamber. The length of the barrel piece was chosen to 160 mm corresponding to the distance from the arc cavity to the freezing cell, when using the CENG-cryostat in combination with the arc chamber. The arc chamber was equipped with graphite electrodes (centre and wall) and Macor insulator and nozzle elements. Slow feed pellets ($200\text{--}300 \text{ bar}\cdot\text{cm}^3$, 50 m/s) were injected into the arc cavity (4 cm^3). The arc was driven in series with the magnet coil by the JET power supply, which was programmed to produce double humped current profile (10 capacitors at first 10 μs , 200 μs pause, 6 cap. at 3 μs , 200 μs pause, 15 cap. at 3 μs ; in all 31 capacitors fired within 416 μs).

Figure V.5 and V.6 shows the arc characteristics and the pressure transients for two shots produced with unchanged external conditions. The size of the feed pellet was $200 \text{ bar}\cdot\text{cm}^3$, as measured from the amount of hydrogen condensed in the feed pellet freezing cell. However, as seen from the recordings of the arc characteristics and the pressure transients, the outcome of these two shots are rather different. At 600 μs (peak pressure) 1100 J has been dissipated by the arc in shot #40 (Fig.V.5)

compared to 900 J in shot #41 (Fig.V.6). This gives a peak pressure of 160 bar in shot #40 as compared to 110 bar in shot #41. More significant is the difference in the barrel pressure transients. In shot #41, with the less effective pellet/arc coupling, the barrel pressure shows strong oscillations at a low frequency. These oscillations are present also at the chamber pressure transient but in opposite phase (Fig.V.7), indicating the presence of a standing wave. Assuming half a wave length in the barrel, a phase velocity of 1.1 km/s may be calculated. For a hydrogen sound wave, this corresponds to a gas temperature of about 215 K. In shot #40, with the stronger pellet/arc coupling, the barrel pressure transient also shows oscillations but at a 3 times higher frequency. This would correspond to a 9 times higher temperature i.e. around 2000 K. These results indicate, that the feed pellet may interact with the arc in different ways from shot to shot even if the external parameters are kept constant. Especially it indicates that pellet fragments may be ejected into the barrel causing a low average barrel gas temperature.

Pressure build-up in closed chamber with fast pellet injection
 These measurements were performed in order to study the pressure build-up in the arc chamber with injection of fast feed pellet. The arc pipe gun for production of fast feed pellets (described in /2/ p. 25) was mounted on the large prototype arc chamber as sketched in Fig.V.8. In these first experiments the out-let from the arc chamber was closed by a valve at the position V in Fig.V.8. The chamber pressure was measured by a transducer at position P. The arc chamber was equipped with a Macor nozzle having a sharp bend of the inlet-line for the fast feed pellet. A molybdenum centre electrode and a graphite lined cylindrical electrode was used. The main arc of the prototype chamber was driven in series with the magnet coil by the JET power supply and the propulsion arc for the feed pellet was driven by the Rise power supply. Hydrogen feed pellets of different sizes (up to 500 bar·cm³) were condensed in the freezing cell of the arc pipe gun. By firing an arc at the end-electrode of the cell, the pellet was injected (in a fragmented state) into the arc chamber, where the pressure transient from the evaporation of the

pellet by the main arc was measured together with the arc characteristics.

Figure V.9 shows data from a shot with a $200 \text{ bar}\cdot\text{cm}^3$ feed pellet. In this shot the main arc (31 capacitors) was fired $300 \mu\text{s}$ after the firing of the pipe gun arc. It is seen that the chamber pressure has a very fast increase rate up to a peak pressure of about 150 bar. Unfortunately the pressure falls off again rather quickly. Almost the same pressure transient is observed for different sizes of feed pellets. With the arc chamber closed the pressure decays to a level around 15-20 bar in about 1 ms. From Fig.V.8 the closed volume including the pipe gun, the inlet channel, the arc cavity and the outlet barrel piece up to the closed valve (V) is calculated to be about 8 cm^3 . From the chamber pressure transient in Fig.V.9 it is seen that a few hundred microseconds after the initial pressure spike, the pressure has decayed to a (oscillating) level of only 50 bar. For an original amount of gas of 200 bar cm^3 (STP) confined in 8 cm^3 this would correspond to a gas temperature of about 600 K.

From earlier experiments with the arc pipe gun in a stand-alone set-up where the output from the gun was studied by means of a microwave mass detector and optical detectors it was found that a head lump of solid pellet material was ejected at a velocity around 1 km/s followed by a tail of additional material. The fast decaying pressure transient of the present experiment (Fig.V.9) could be explained by this output characteristics of the arc pipe gun: When the head lump of condensed hydrogen material arrives at the arc chamber it is evaporated by the main arc, whereby the initial pressure spike is produced. This pressure spike will however act on the tail of hydrogen material following the head lump from the pipe gun such as to prevent the tail material to enter the arc chamber cavity and to contribute to the pressure build-up. This behaviour could probably be avoided if the ignition of the main arc could be delayed until all the pellet material from the arc pipe gun had entered the arc cavity. However, in shots where the ignition time of the main arc was delayed to after the time of arrival of the head lump of the feed pellet no ignition could be produced. This is to be expected with the present ignition scheme, which only allow

ignition at an initial pressure below around 10 bar. In the shots with delayed ignition time the pressure in the arc chamber had probably risen to above this level, thereby preventing ignition. With another ignition scheme (e.g. a low power pre-ignition of the main arc until all of the feed pellet material has entered the cavity, and thereafter high power arc) this problem may be circumvented.

Instead of changing the ignition scheme in the fast feed-pellet injection experiment we have tried to improve the efficiency by changing the electrode geometry of the arc chamber. In the experiments described above the initial very fast rising chamber pressure is believed to blow a substantial part of the feed pellet back into the pipe gun. In order to prevent a strong initial interaction between the feed pellet and the arc, the electrode geometry was changed such as to prevent the arc to stay at the cylindrical cavity wall, along which the feed-pellet enters the cavity. This was done by replacing the conducting graphite liner of the cylindrical wall with an insulating Macor liner and at the same time replacing the insulating Macor nozzle with a conducting stainless steel nozzle. In this way the arc would run from the central electrode to the nozzle element rather than to the wall.

With otherwise the same set-up as described above the results shown in Fig.V.10 and V.11 were produced. Figure V.10 shows results from a shot with the arc chamber closed and Fig.V.11 with open barrel (no projectile pellet). Feed-pellets of $600 \text{ bar}\cdot\text{cm}^3$ were used in these shots.

VI. SUMMARY AND CONCLUSION

The objective of the project described in this report and in /1/ and /2/ was to investigate acceleration of deuterium pellets ca. 3 mm in diameter towards achieving pellet velocities clearly in excess of 2 km/s and exploiting the limits of the arc heated gas gun to obtain design parameters for a possible pellet injection into JET. The first attempt to fulfil this objective is described in detail in /1/. The set-up consisted of a cryogenic

arc chamber where hydrogen vapour was condensed on the arc chamber walls before the discharge was fired. Although a fairly small power supply (1 kJ) was used, pellet velocities up to 1500 m/s were obtained and these results were found encouraging enough to go on with a design and construction of a larger power supply (20 kJ). It was, however, also recognised that a high acceleration of the pellet was only obtained at the very beginning of its motion along the gun barrel, which indicated a high heat loss from the arc heated gas to the barrel.

During the work described in /2/ it was recognised that when increasing the energy input to the arc in order to increase the pellet velocity further, the heat input to the extrusion/punching pellet loading mechanism was found to be critical: preparation of pellets became difficult and cooling times between shots became inconveniently long. To circumvent this problem the concept of a room temperature hydrogen propellant pellet fed arc chamber was proposed. Preliminary result from acceleration of polyurethane pellets with a prototype of this arc chamber was described in /2/ as well as the work of developing of feed pellet guns for this chamber and design considerations for a high pressure propellant pellet fed arc chamber.

In this report the final set-up is described together with the obtained experimental results. For the pellet fed case it was found to be impossible to keep up the pressure for a sufficiently long time to produce a steady acceleration providing velocities above 2 km/s. Furthermore, pellets were broken in attempts to reach velocities above 2 km/s. A detailed investigation of the cause for the pellet breaking was not possible to perform partly due to the very unreproducible pressure performance of the arc chamber. It could be due to the high pressure pulse on the pellet in the beginning of the acceleration, or it could be the fact that the pellet is rolling on the inner wall of the barrel after that the diameter of the pellet has been worn down due to the friction between barrel wall and pellet surface. It was expected that it should have been possible to keep up the pressure behind the pellet for a longer time than it has turned out. This indicates strongly that the gas behind the pellet which is heated by the arc discharge, loses its temperature by

heat conduction to the wall. Furthermore, several experiments show an extremely small efficiency for the pellet energy compared to the delivered electrical energy deposited in the arc.

For the fast feed-pellet injection experiment it was found that although a more adequate pressure transient (max. 175 bar) was produced the pressure level was still below what was obtained in earlier experiments with slow feed-pellet injection (max. 200 bar), and the duration of the pressure pulse did not increase significantly by this technique, probably for the same reasons as mentioned above.

For the gas fed case it was found, that when using the 300 bar valve at its full capacity in connection with the arc chamber, a maximum velocity of about 1800 m/s could be obtained, however, many pellets were broken. With 300 bar from the valve but without igniting the arc, a velocity of about 1300 m/s was obtained. This may be compared with results obtained with the 300 bar valve connected directly to the barrel (omitting the arc chamber). In this case acceleration with 300 bar produced pellet velocities up to about 1900 m/s. It may be concluded that the advantages obtained by arc heating of the gas from the fast valve by the arc chamber, are more than eliminated by the disadvantageous effect of the increased flow impedance and dead volume, introduced by the arc chamber.

For both cases it may be concluded that sufficiently high average gas temperature and pressure were not reached.

ACKNOWLEDGEMENTS

This work was done under an Art.-14 contract between JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory. Ideas and comments to the work from the JET Project Monitor, Dr.P.Kupschus and from Dr.K.Sonnenberg are greatly acknowledged.

REFERENCES

1. S.A.Andersen, J.Bundgaard, V.O.Jensen, A.Nordskov, B.Sass, H.Sørensen, K.V.Weisberg, "Investigation of Pellet Acceleration by an Arc heated Gas Gun", An Interim Report on the Investigations carried out to 31 August 1985, Risø-M-2536.
2. P.Andersen, S.A.Andersen, J.Bundgaard, L.Bekmark, B.H.Hansen, V.O.Jensen, H.Kossek, P.K.Michelsen, A.Nordskov, B.Sass, H.Sørensen, K.V.Weisberg, "Investigation of Pellet Acceleration by an Arc heated Gas Gun", An Interim Report on the Investigations carried out from September 1 1985 to March 31 1987, Risø-M-2640.
3. J.Lafferranderie et al., 14th Symposium on Fusion Technology, 8-12 September, Avignon, France, Proceedings 2, 1367-1373.

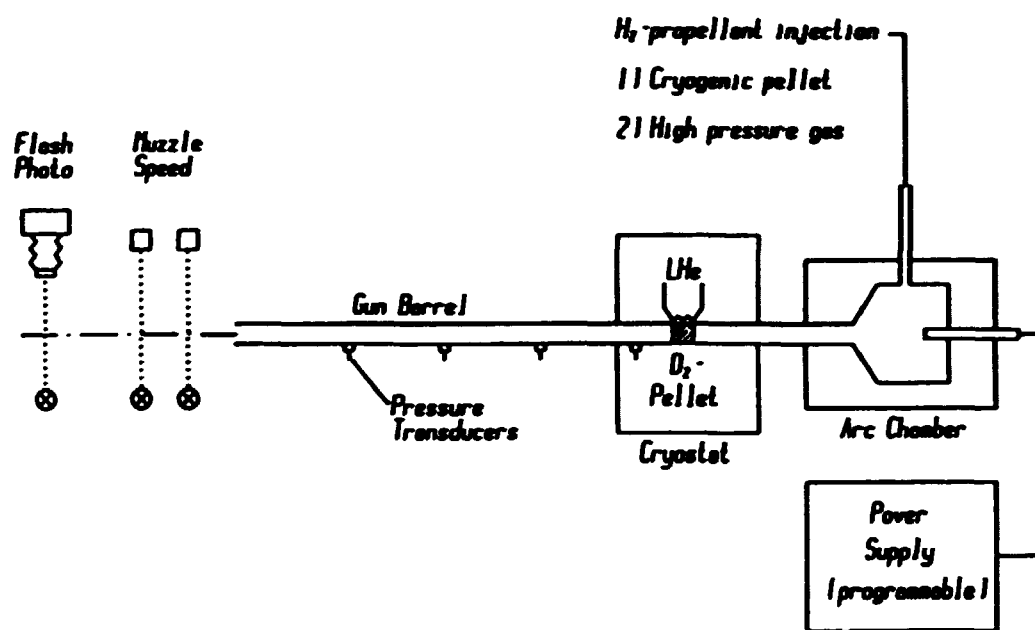


Fig.II.1: Experimental Set-up

Arc Discharge Circuit

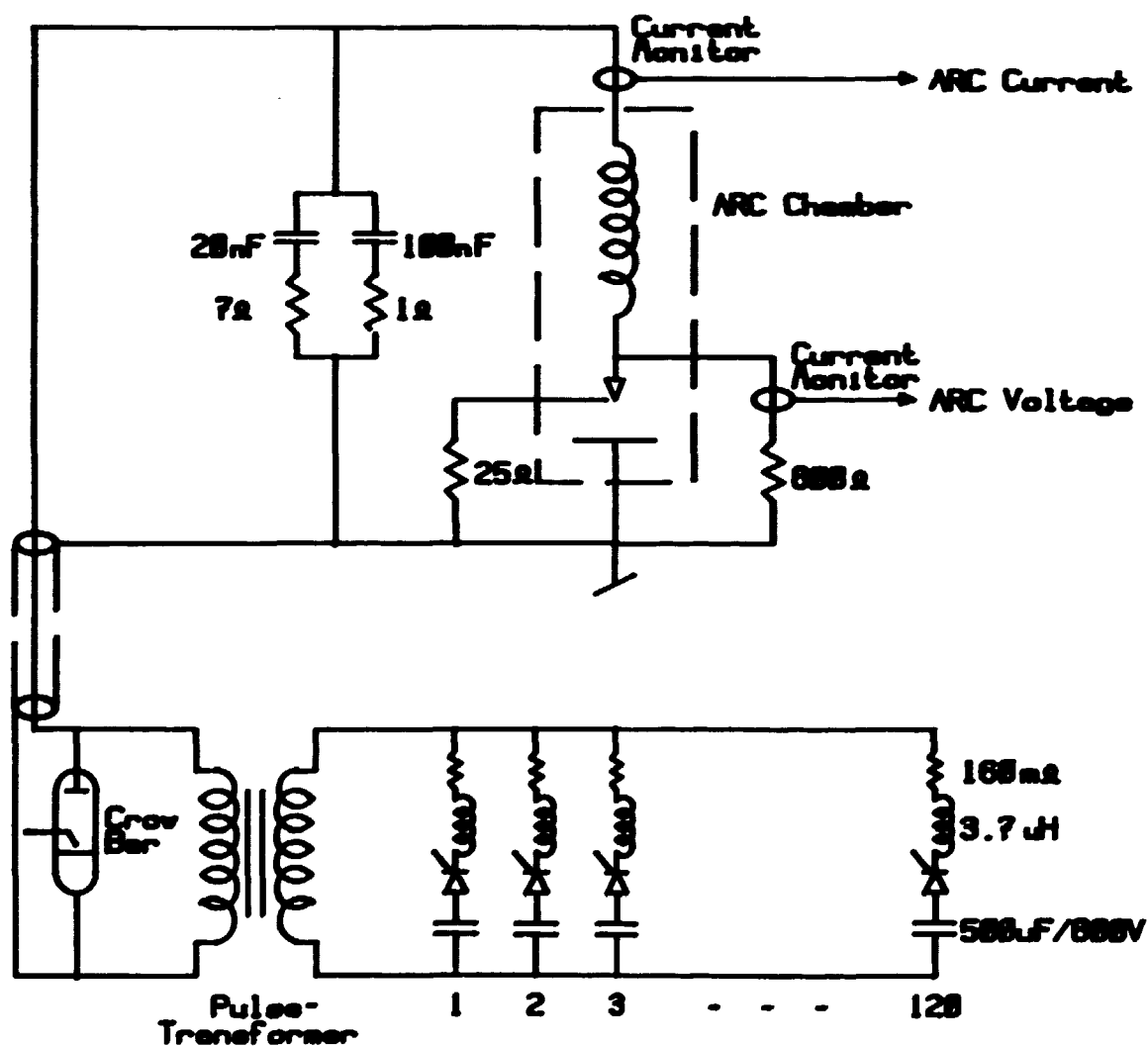


Fig.II.2: A simplified diagram of the JET designed power supply including the arc chamber and the principle of current and voltage measurements

SHOT # 87042705
VELOCITY VS. POSITION

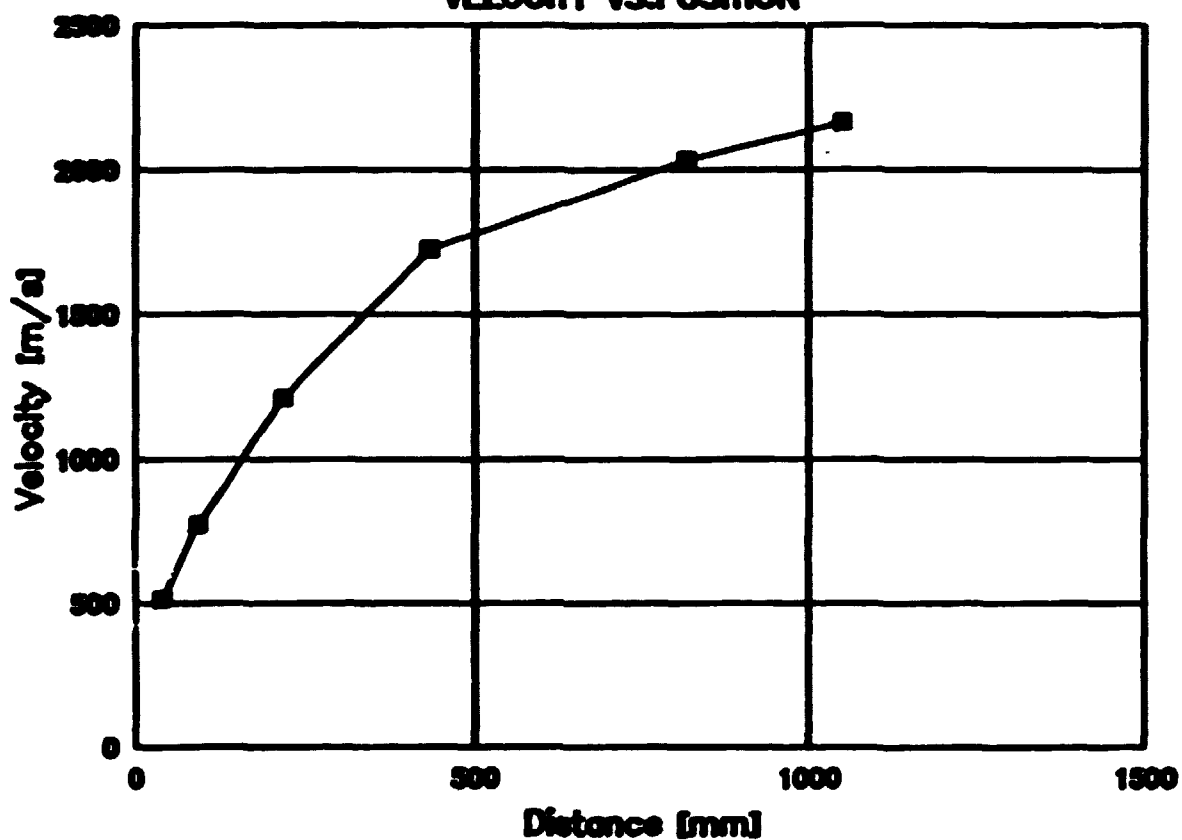


Fig.III.1: Velocity as a function of distance for a shot with a polystyrene pellet

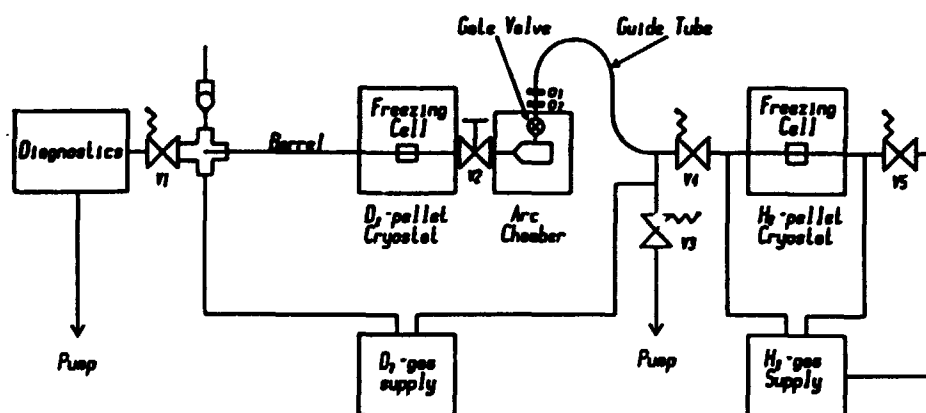


Fig.III.2: Gas supply system

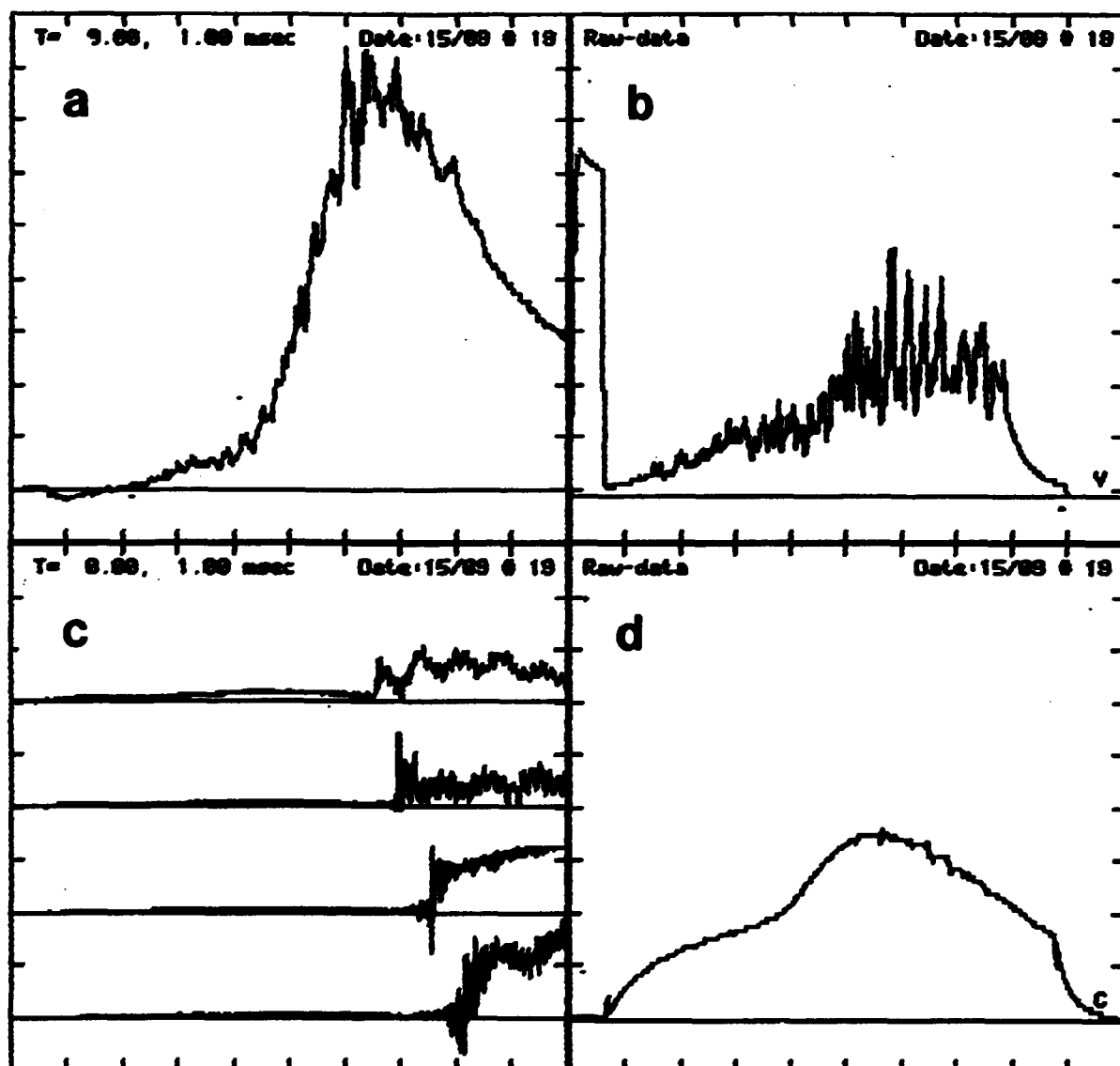


Fig.III.3: Data from shot with arc power supply programmed as shown in Fig.III.5. a:chamber pressure (25 bar/div), b:arc voltage (385 V/div), c:pressure signals along the barrel/uncalibrated), d:arc current (1 kA/div), sweep 0.1 ms/div

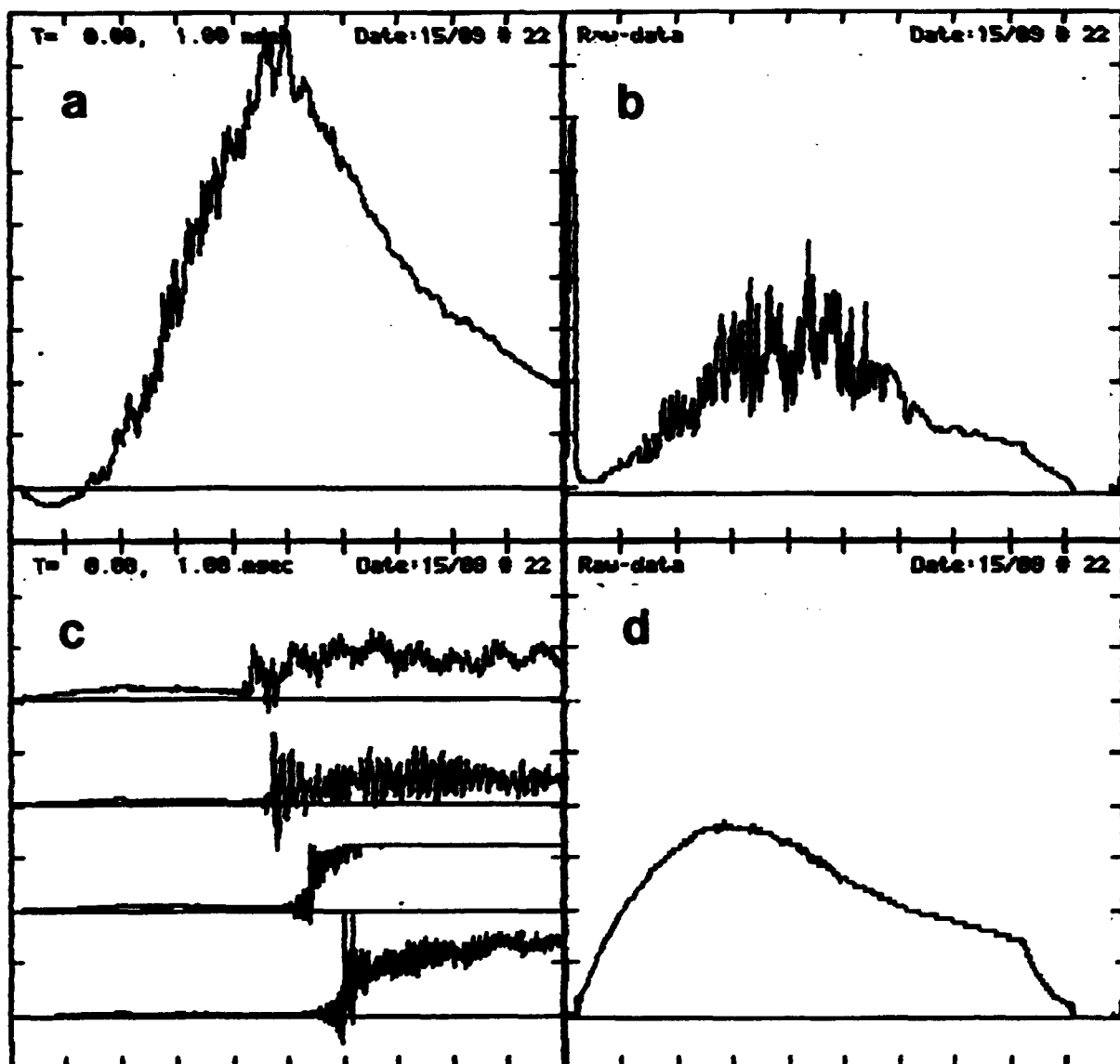


Fig.III.4: Data from shot with arc power supply programmed as shown in Fig.III.6. Scaling as in Fig.III.3

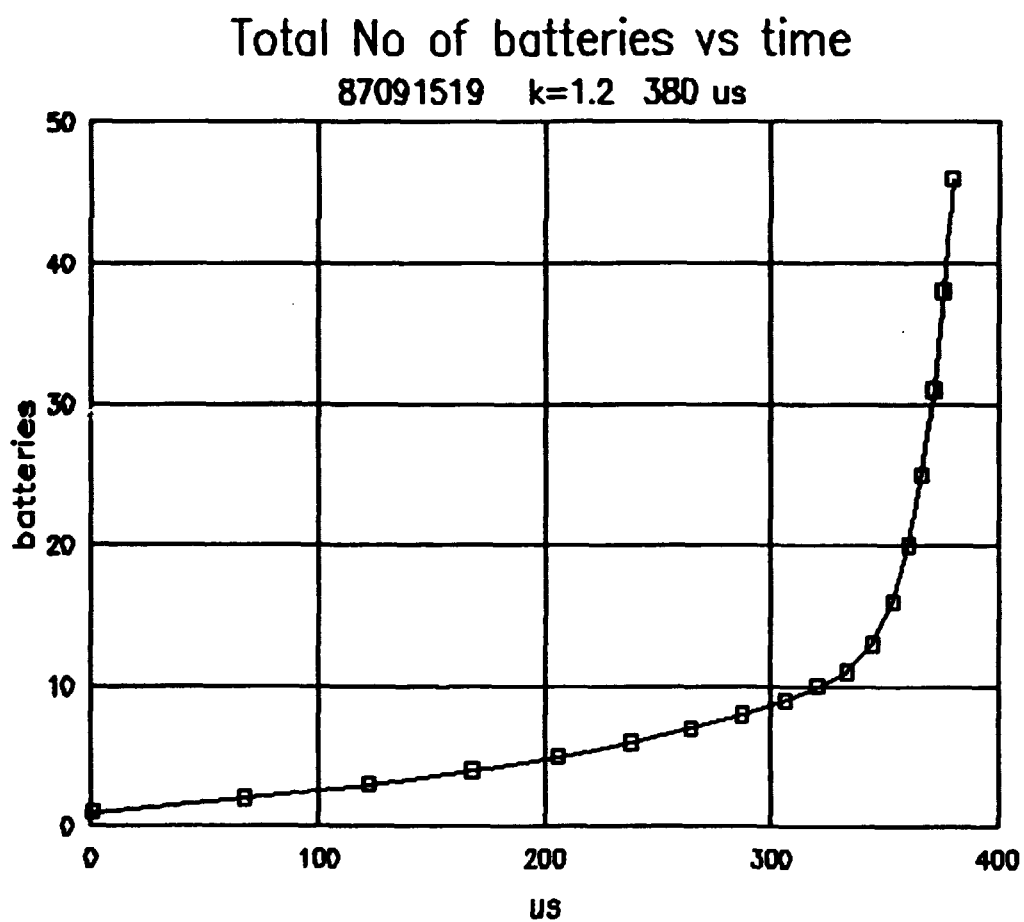


Fig.III.5: Temporal distribution of the triggering of the capacitor bank used for the shot in Fig.III.3

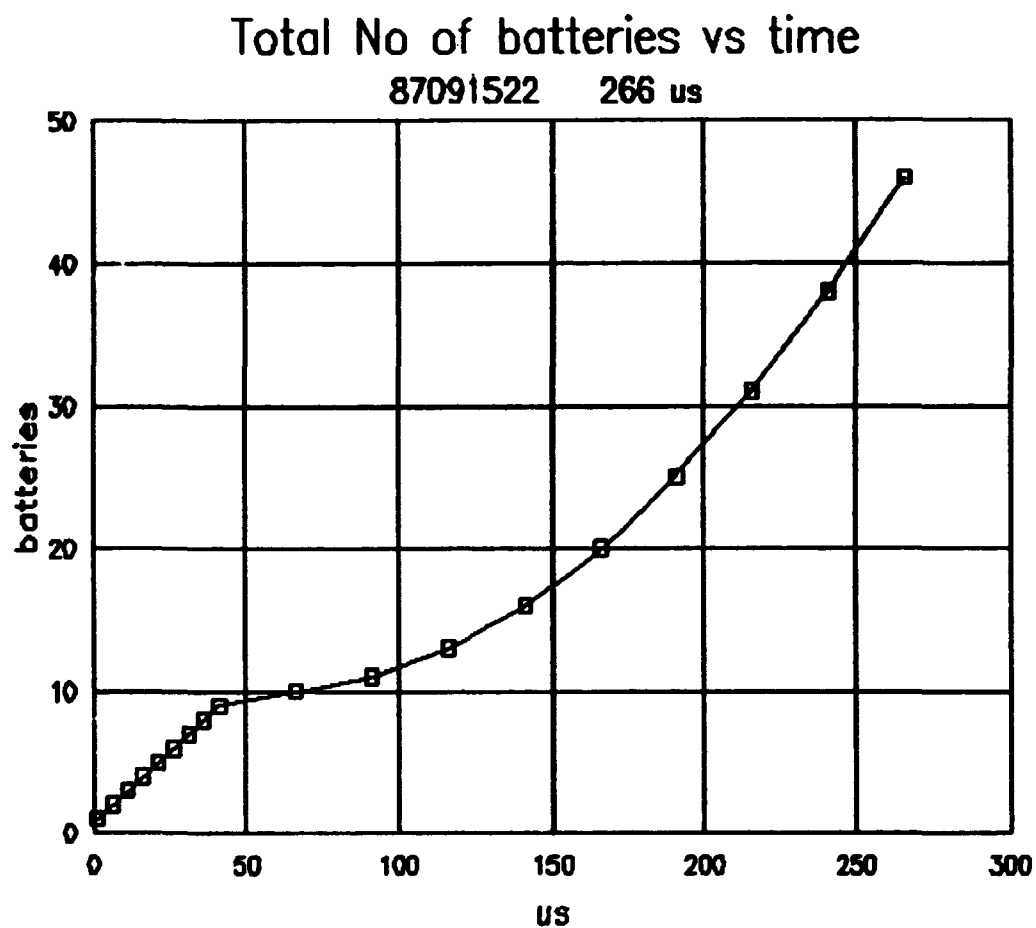


Fig.III.6: Temporal distribution of the triggering of the capacitor bank used for the shot in Fig.III.4

ARC ACCELERATION

#87091519

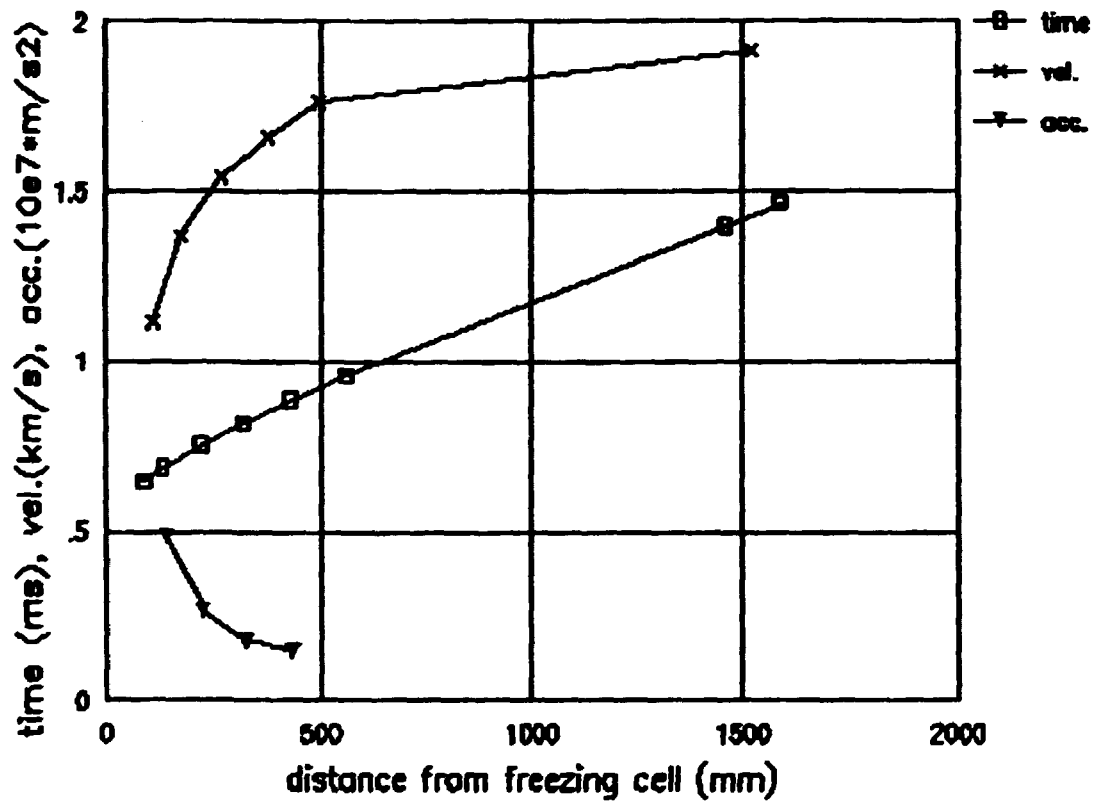


Fig.III.7: Same shot as Fig.III.3. (□):timing signals (ms), (x):velocity (km/s), (▽):acceleration ($\times 10^7 \text{ m/s}^2$) versus distance from freezing cell (mm)

#87091522 ARC ACCELERATION Time, Velocity and Acceleration vs Barrel Position

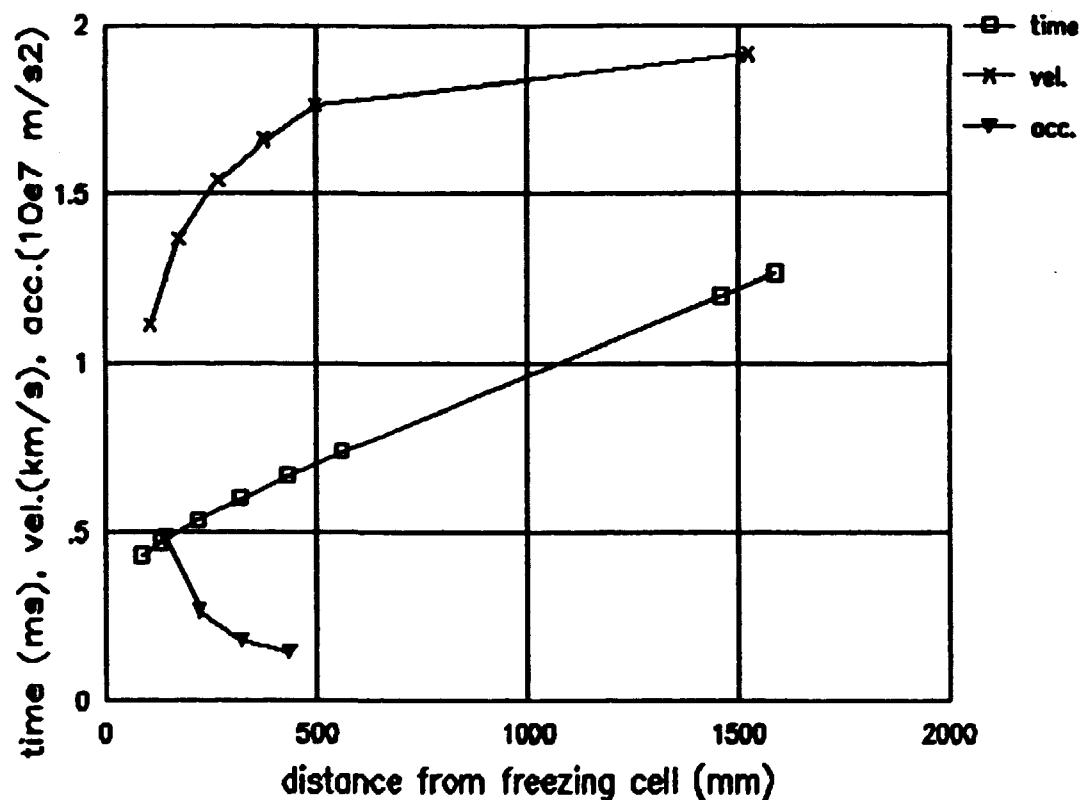


Fig.III.8: Same shot as Fig.III.4. (□):timing signals (ms), (x):velocity (km/s), (▽):acceleration ($\times 10^7 \text{ m/s}^2$) versus distance from freezing cell (mm)

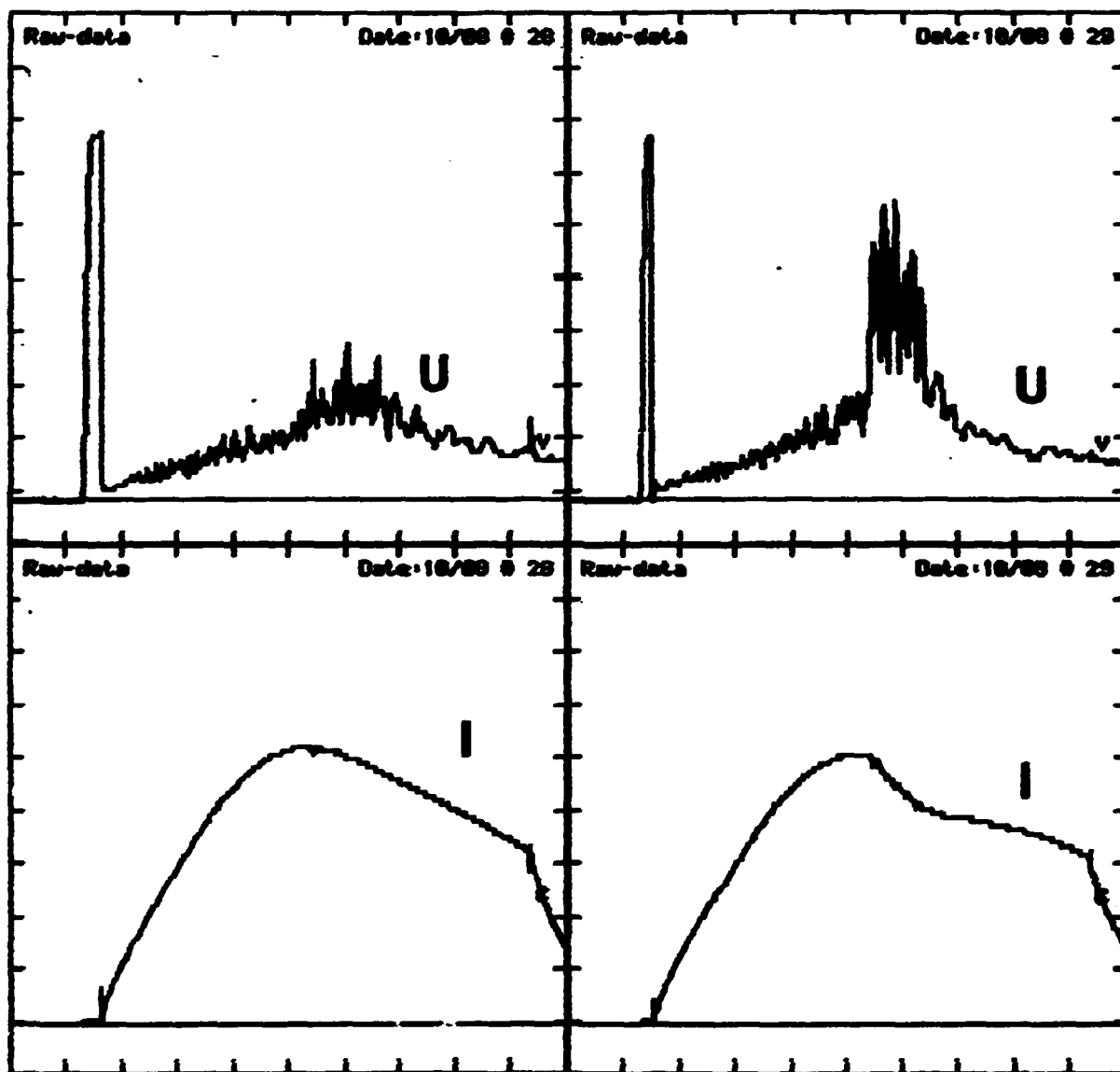


Fig.III.9: Arc current (I,1 kA/div, voltage (U,400 V/div) and chamber pressure (P,25 bar/div) for two different shots #28 and # 29

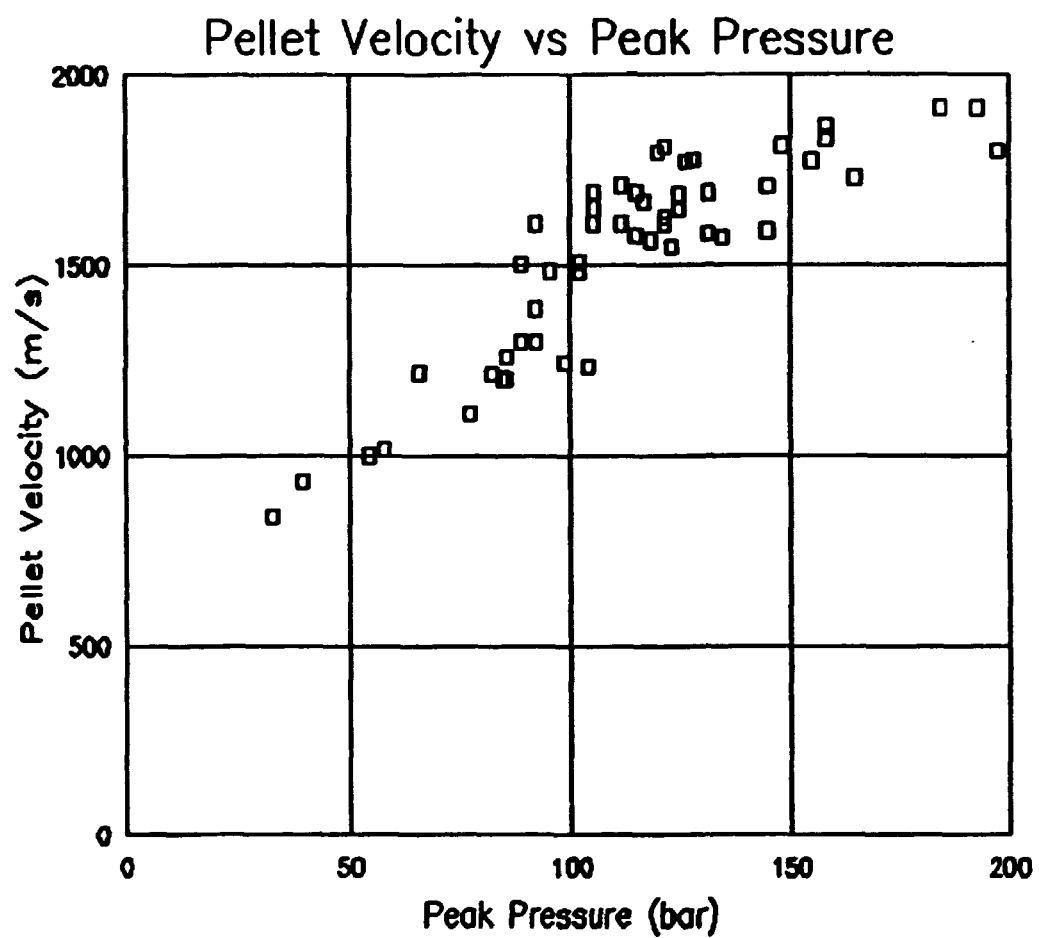


Fig.III.10: Pellet velocity versus peak pressure

Peak Pressure vs Power

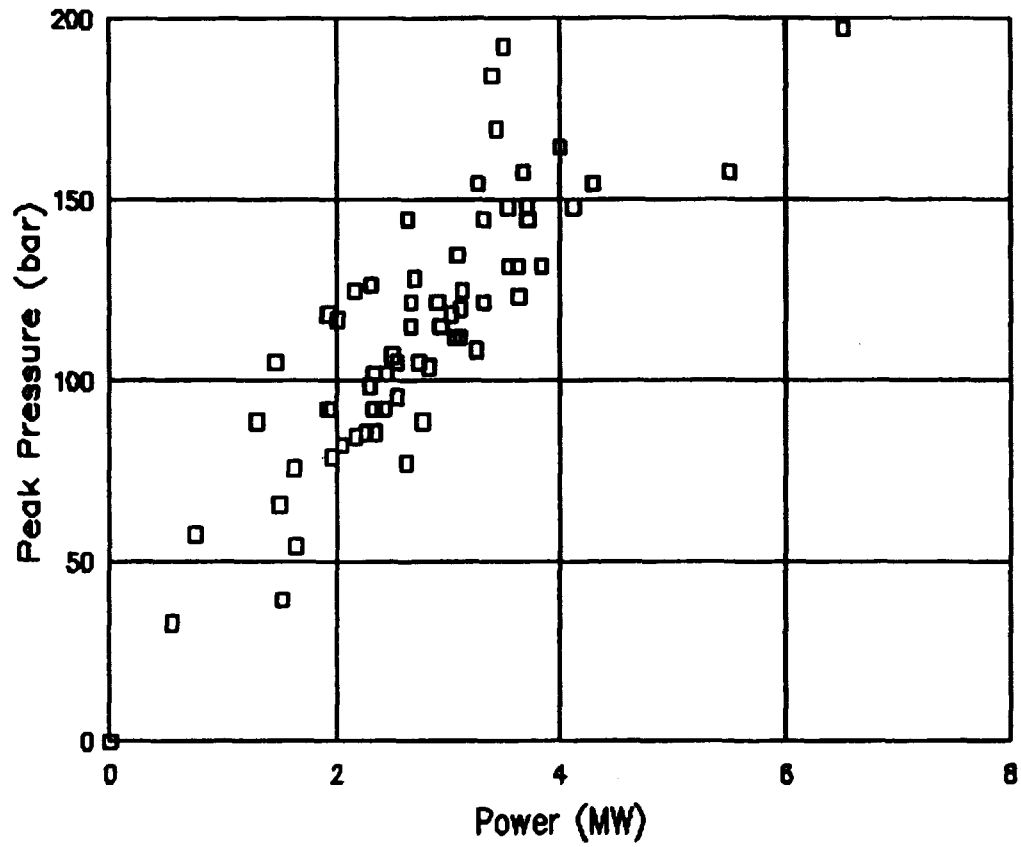


Fig.III.11: Peak pressure versus power

graph #3 Velocity vs. Power
8-10-11-15-16-18-SEP-1987

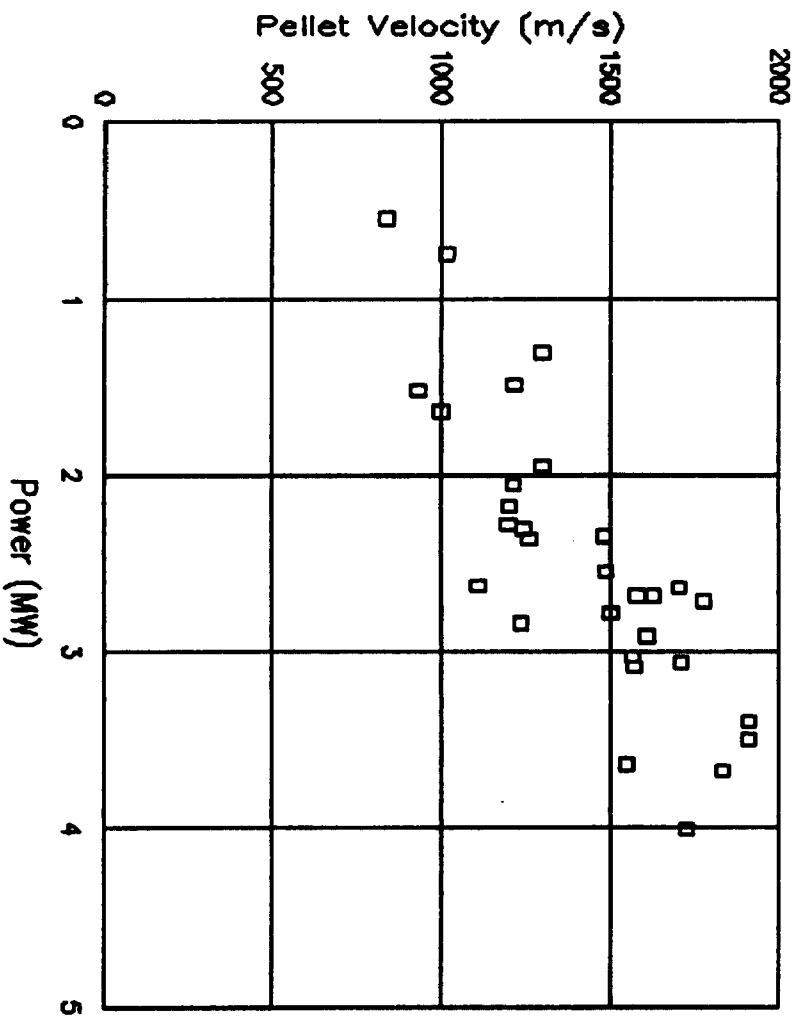


Fig.III.12: Pellet velocity versus power

graph #4 Power vs. Current
8-10-11-15-16-18-SEP-1987

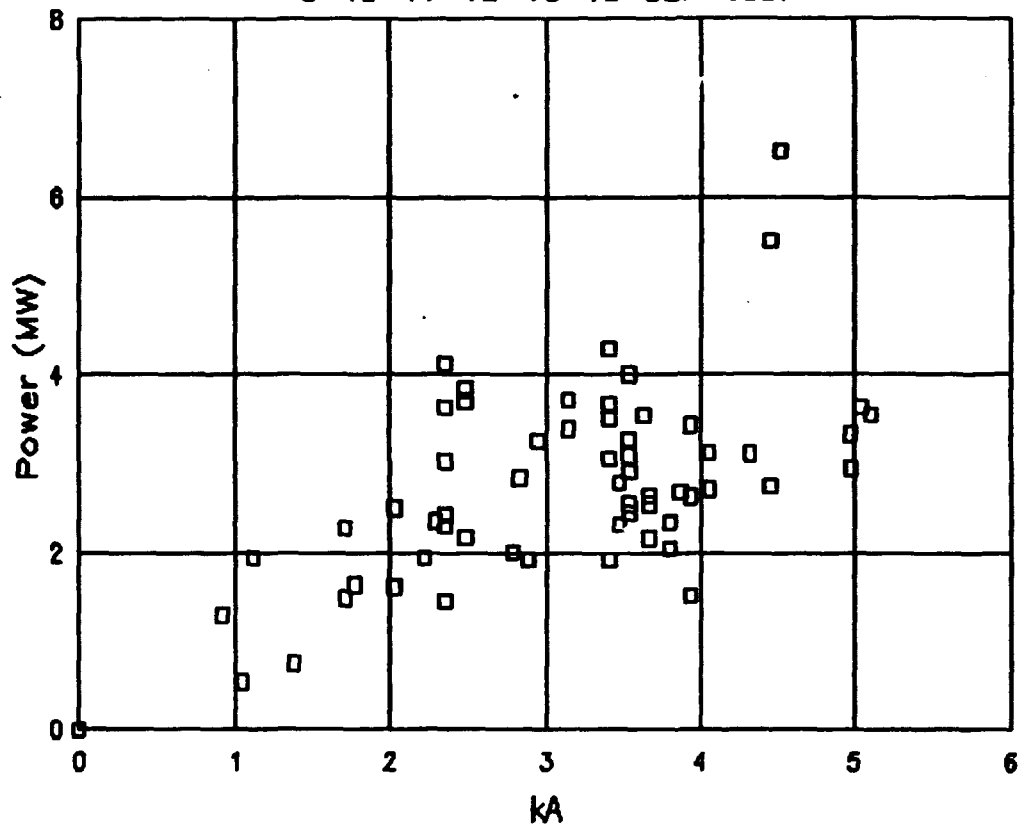


Fig.III.13: Power versus arc current

graph #6 Voltage vs. Current
8-10-11-15-16-18-SEP-1987

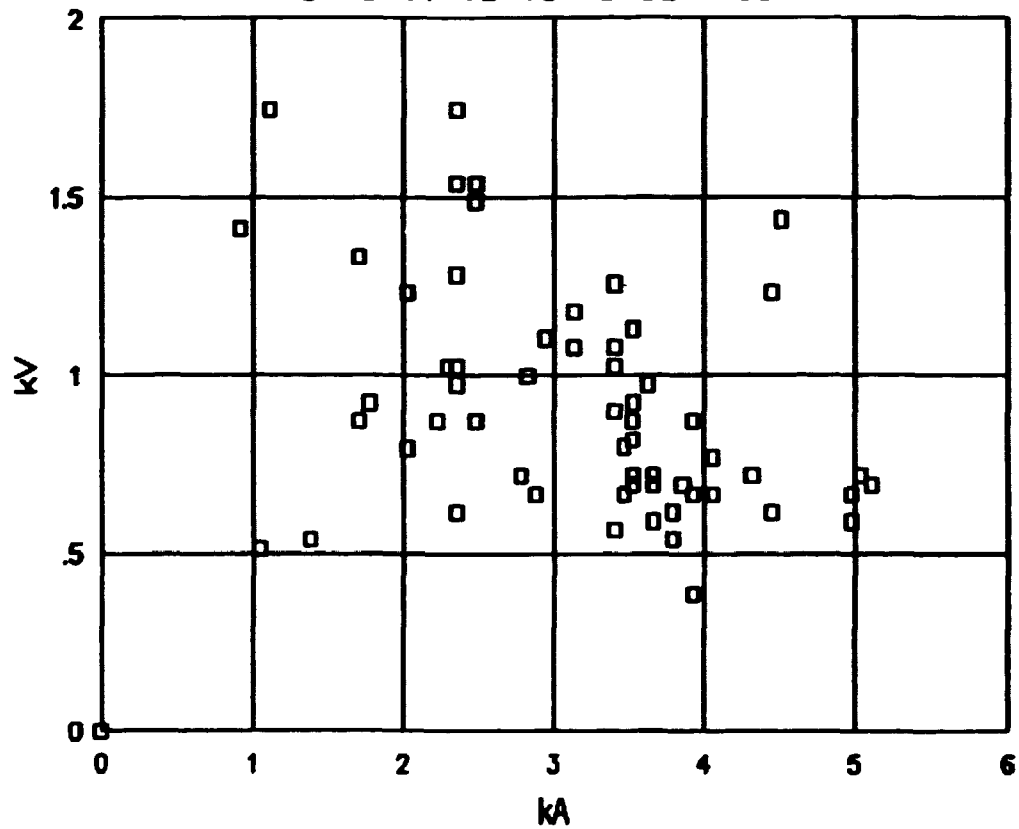


Fig.III.14: Voltage versus arc current

graph #7 Voltage/Current vs. Current
8-10-11-15-16-18-SEP-1987

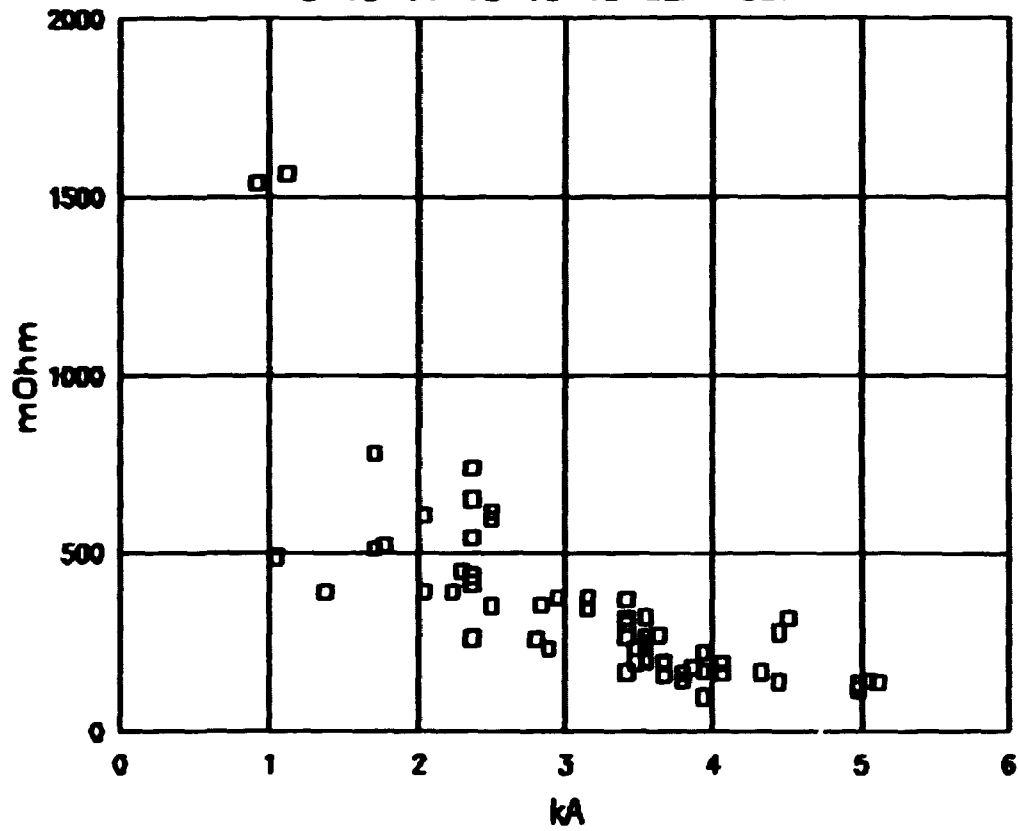


Fig.III.15: Arc resistivity versus arc current

Set-up for 300 bar fast valve injection

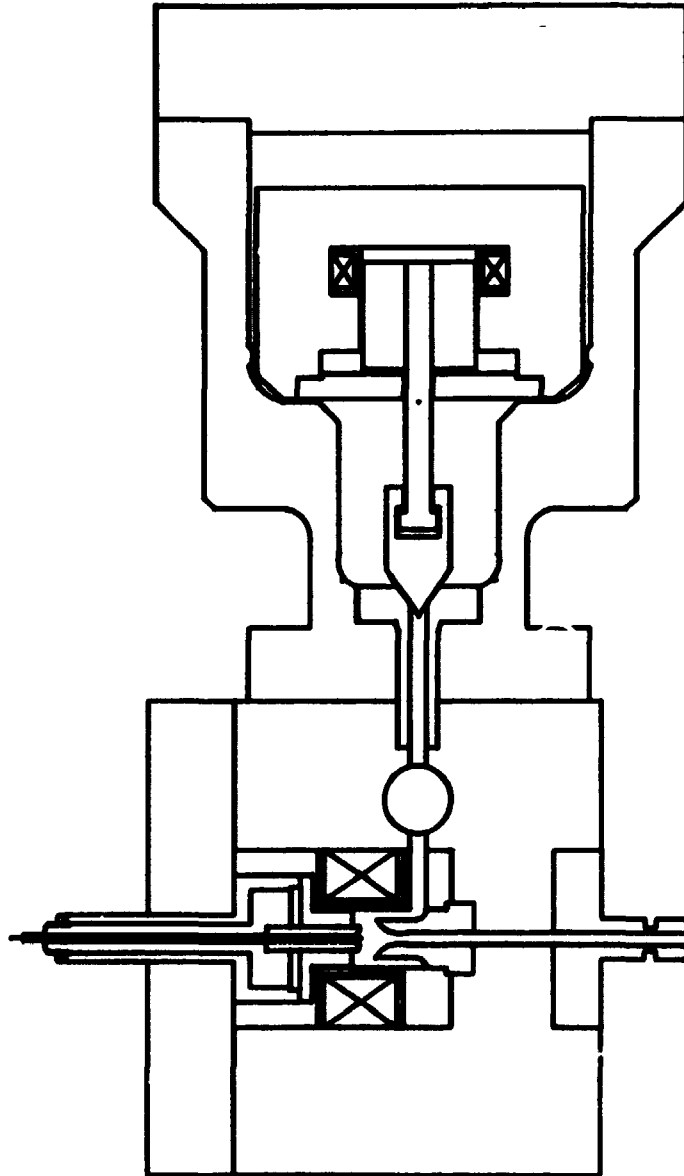


Fig.IV.1: Set-up for 300 bar fast valve injection

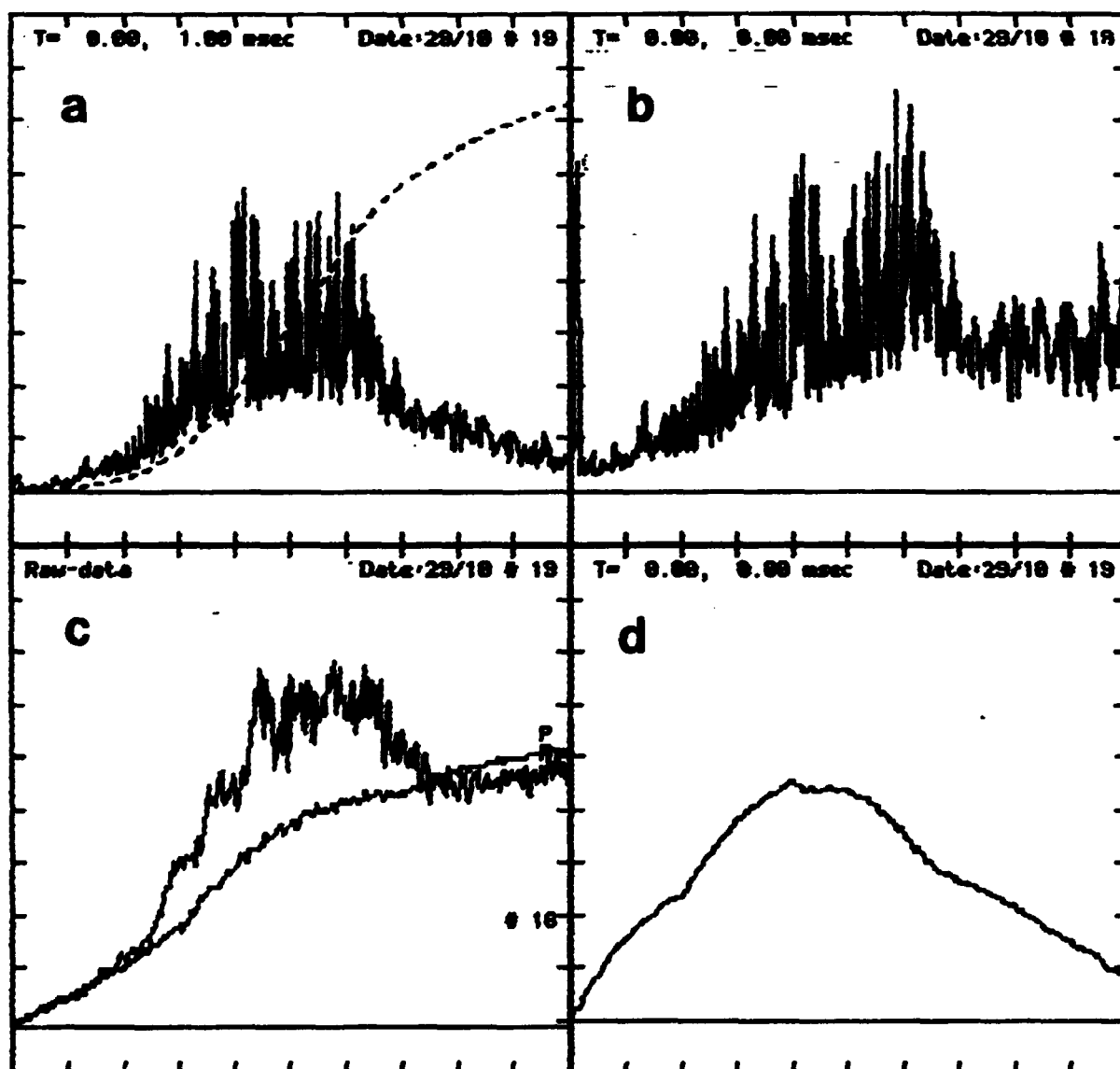


Fig.IV.2: Data from shot with 155 bar valve pressure. a:(solid line) power (1 MW/div), a:(dashed line) energy (200 J/div), b:voltage (385 V/div), c:chamber pressure with and without arc (30 bar/div), and d:current (0.5 kA/div), sweep 0.1 ms/div

#87102919 FAST VALVE/ARC ACCELERATION

Valve pressure 150 bar, 20 batt., 780 V, 300 us

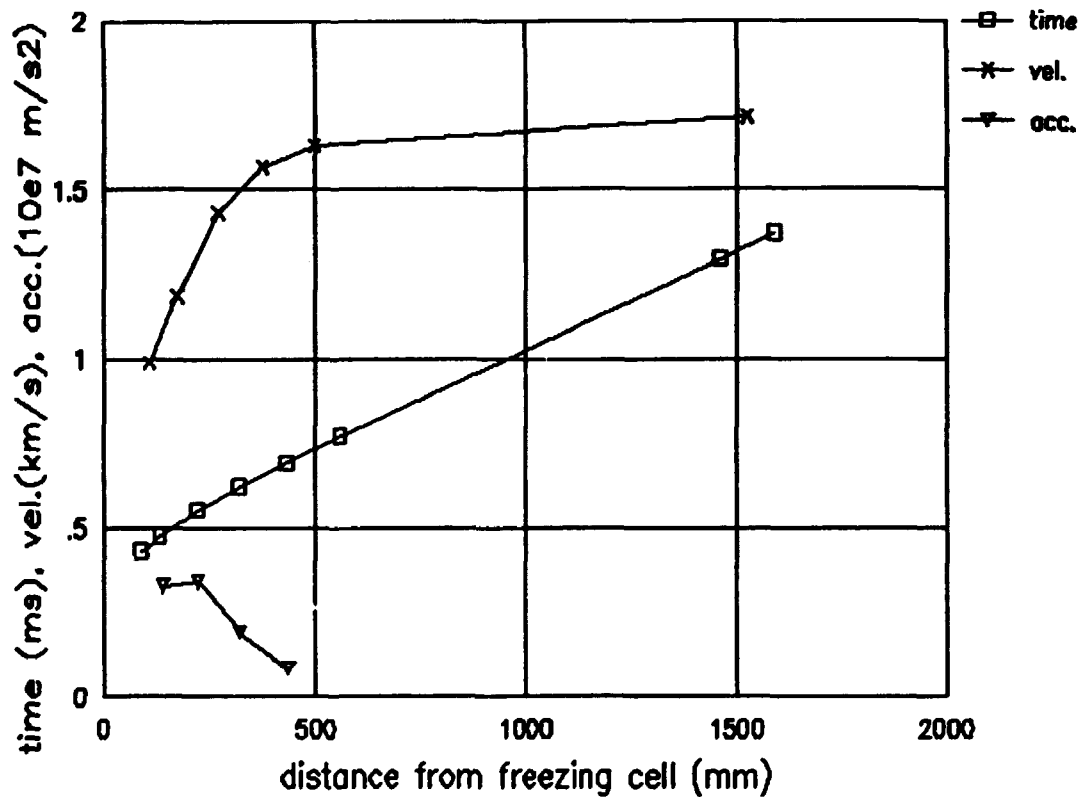


Fig.IV.3: Same shot as Fig.IV.2. (\square):timing signals (ms), (\times):velocity (km/s), (\circ):acceleration ($\times 10^7$ m/s 2) versus distance from freezing cell (mm)

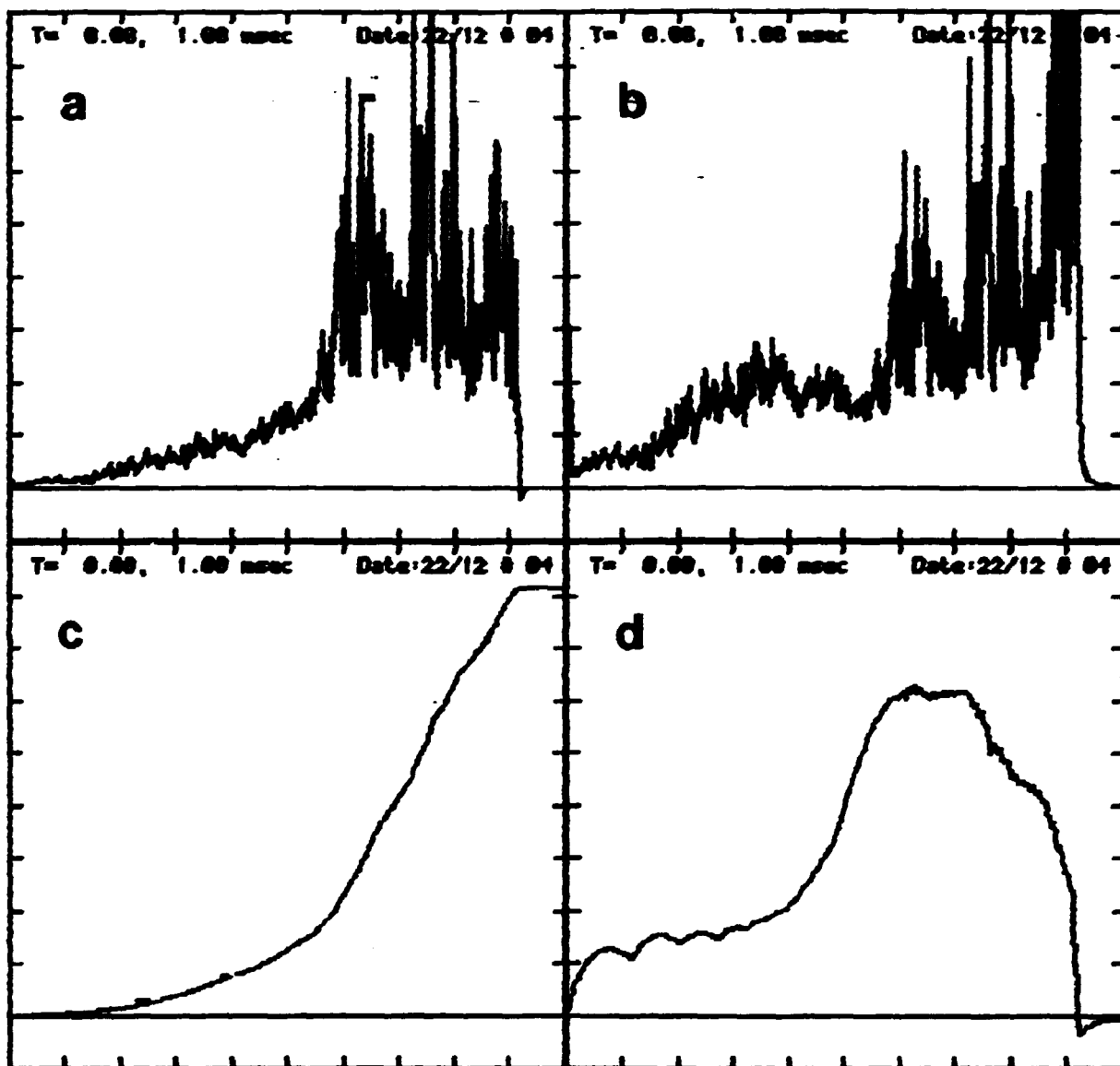


Fig.IV.4: Arc data for shot with gas fed arc chamber, a:power (1 MW/div), b:voltage (400 V/div), energy (200 J/div), and d:current (500 A/div), sweep 0.1 ms/div

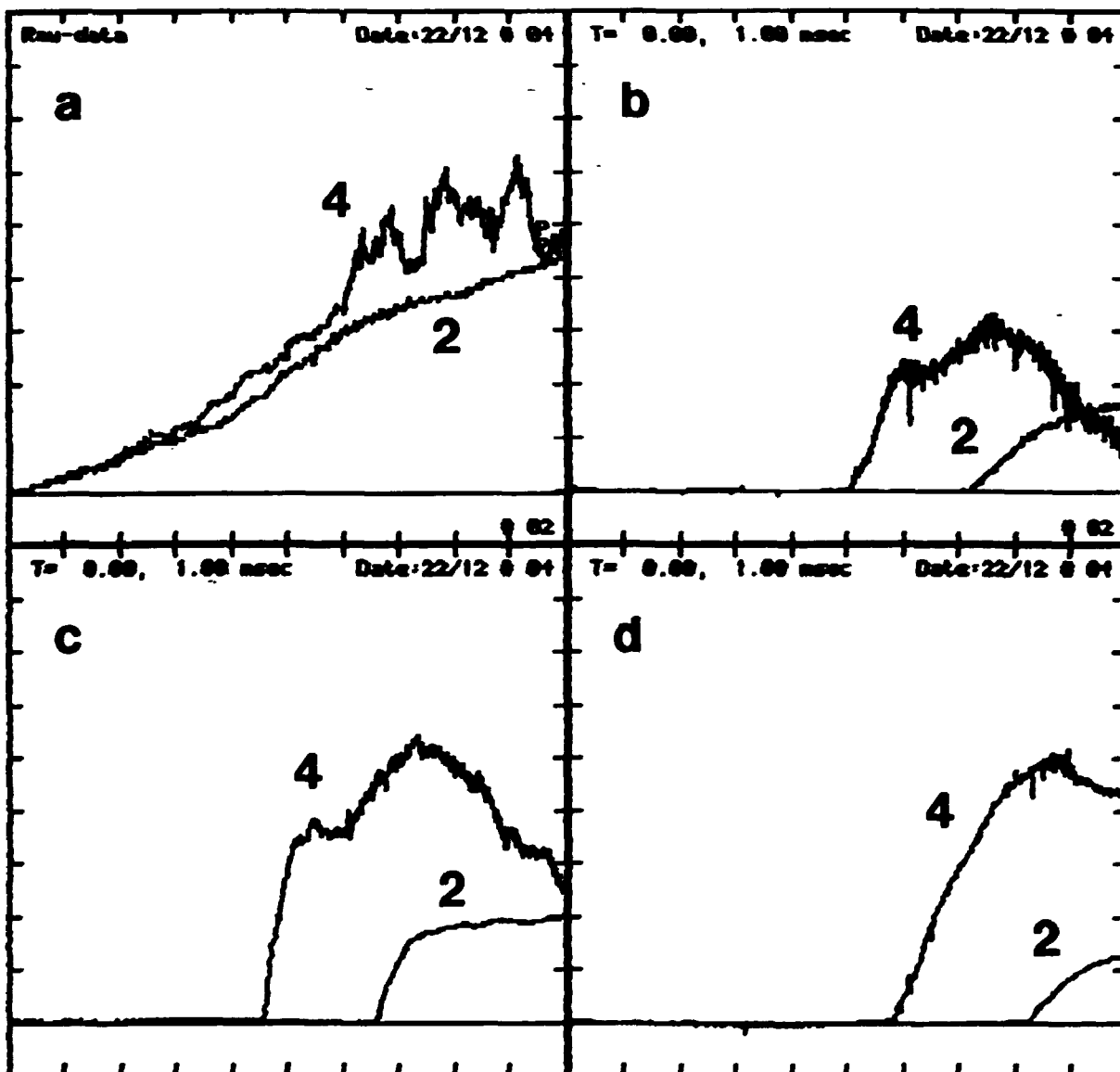


Fig.IV.5: Pressure signals: 2:without arc, 4:with arc. a:arc chamber (60 bar/div), b-d:3 positions along the barrel (20 bar/div), b:x=130 mm, c:x=86 mm, d:x=219 mm.

#87122204 Fast Valve/Arc Acceleration

300 bar, 38 cond., 490 s, k=1.3

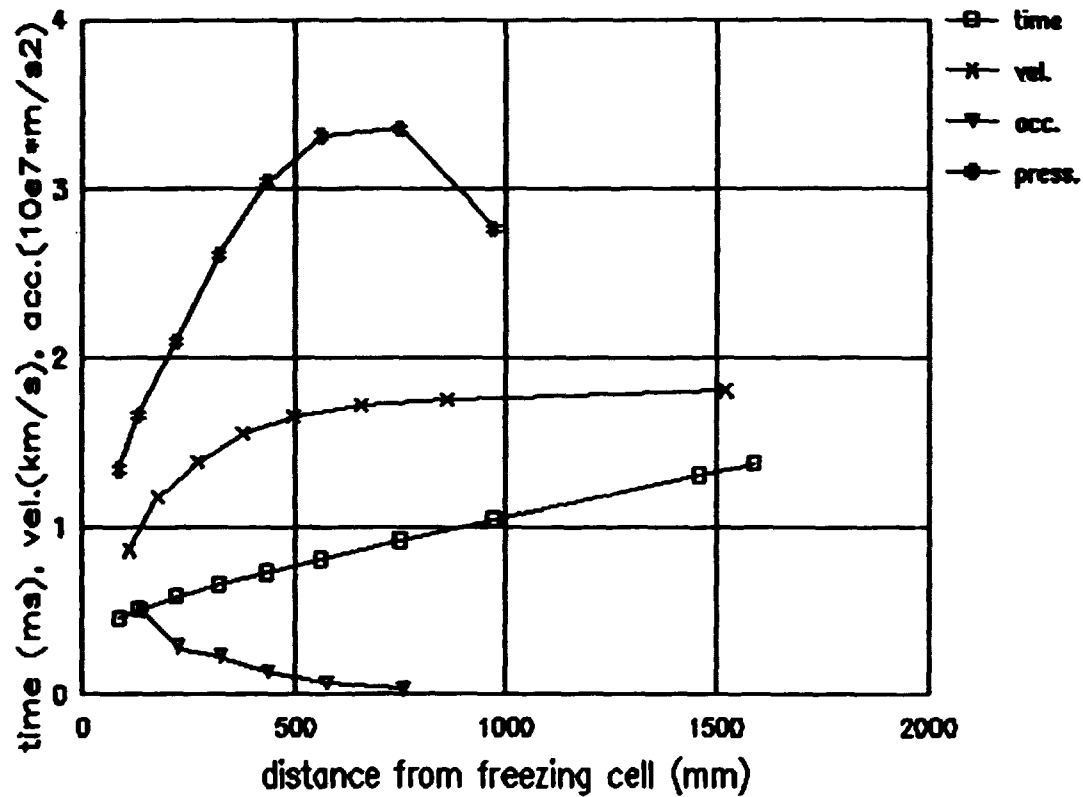


Fig.IV.6: Same shot as Fig.IV.5. (□):timing signals (ms), (x):velocity (km/s), (▽):acceleration ($\ast 10^7 \text{ m/s}^2$), and (#):chamber pressure ($\ast 100 \text{ bar}$) versus distance from freezing cell (mm)

#87121625 Fast Valve Acceleration 300 bar

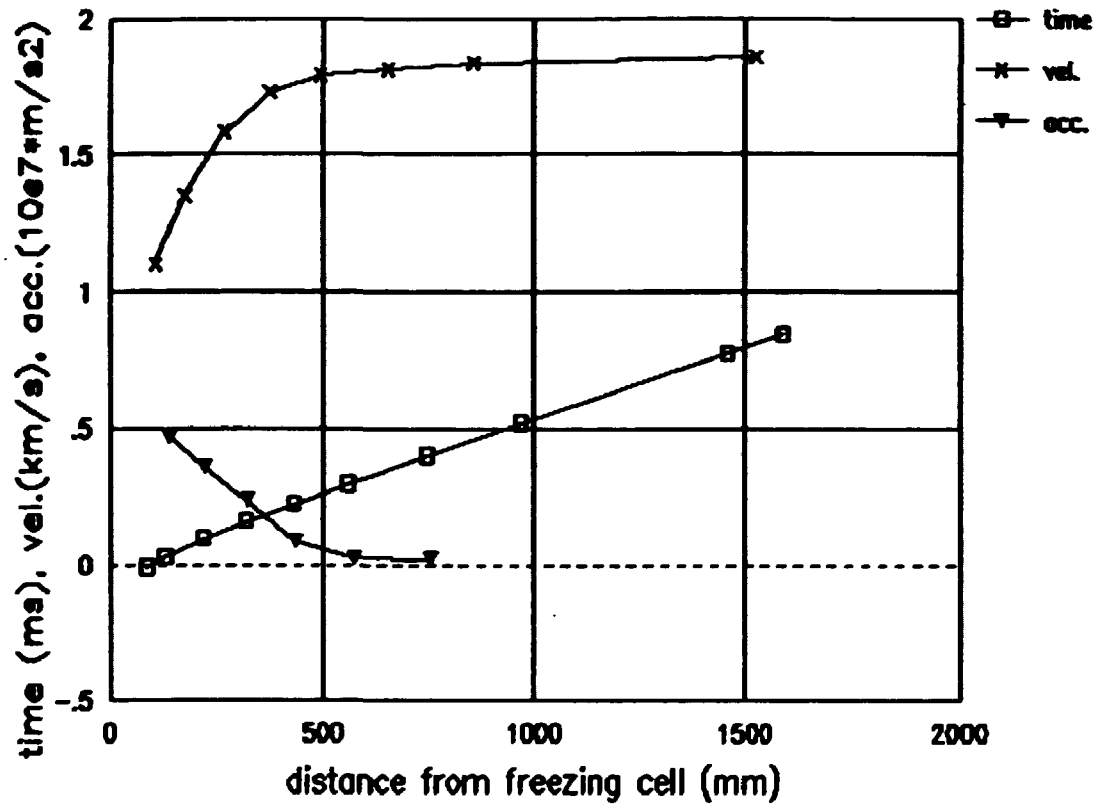


Fig.IV.7: A shot similar to Fig.IV.6, but for a case with the fast valve connected directly to the barrel

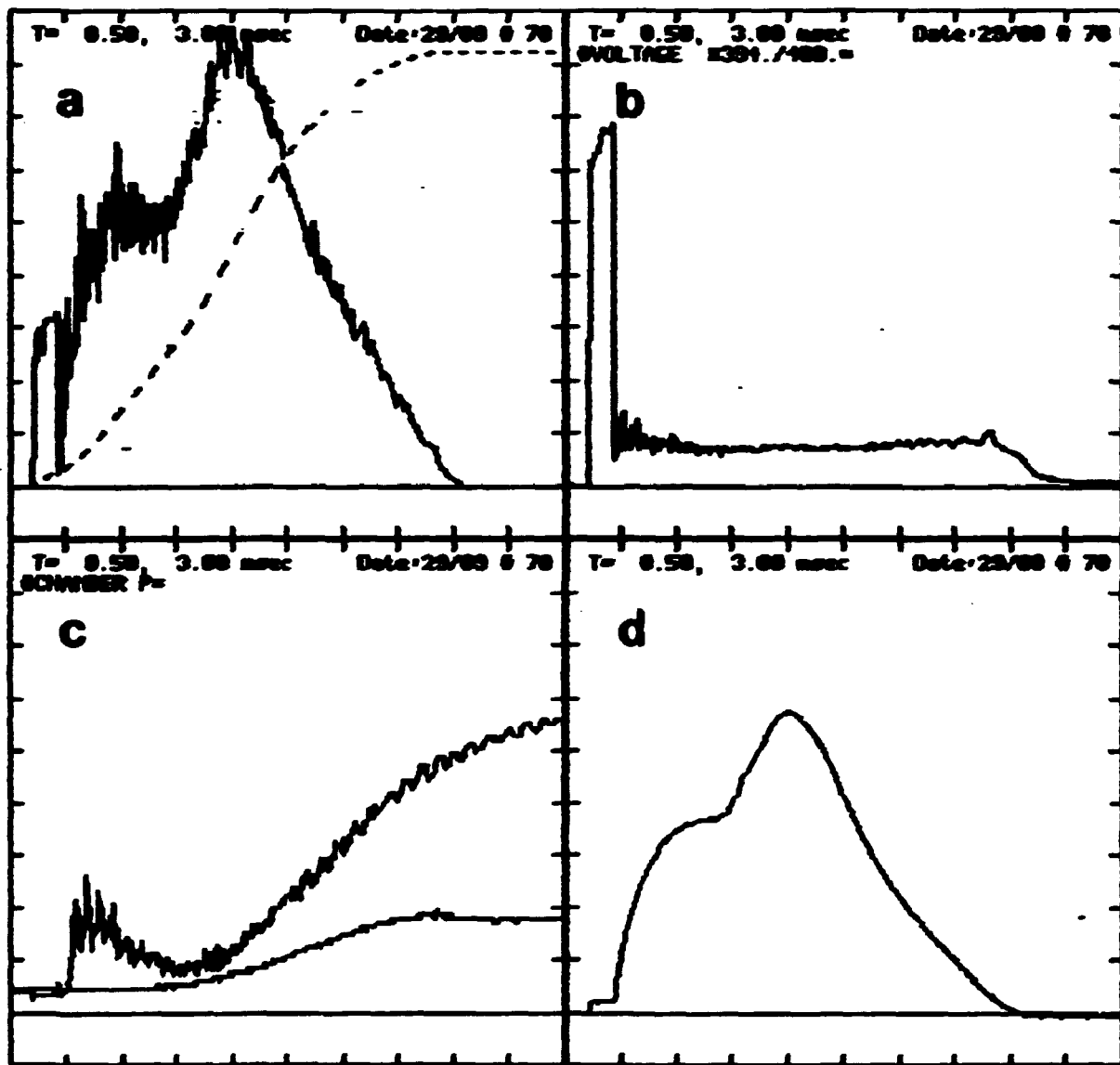


Fig.V.1: Shot with an initial pressure of 40 bar in the valve.
a:(solid line) power (0.1 MW/div), a:(dashed line) energy (100 J/div),
b:voltage (394 V/div), c:chamber pressure (5 bar/div),
and d:current (500 A/div), sweep 0.25 ms/div

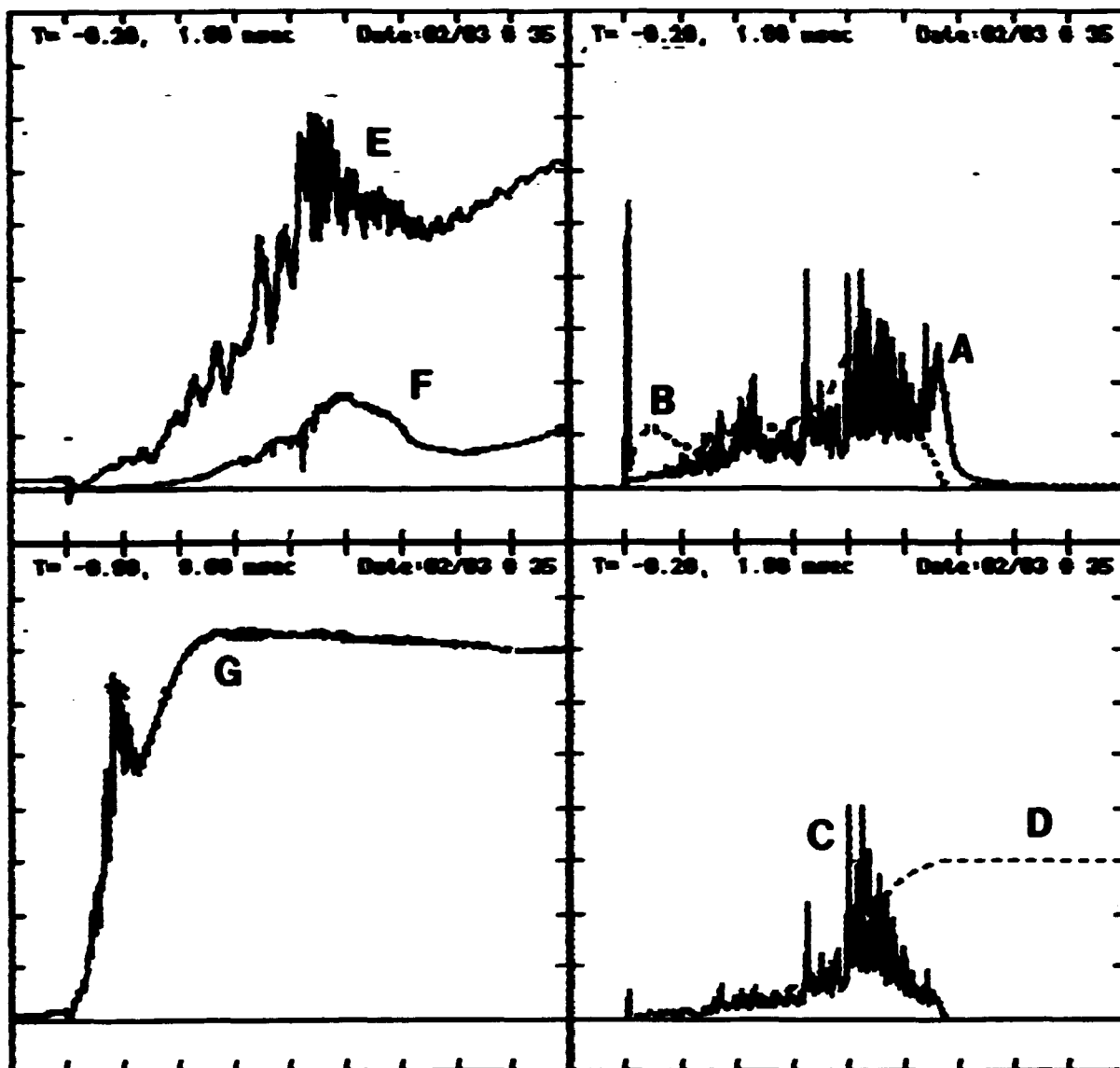


Fig.V.2: Shot with 8 capacitors discharged during 800 μ s. A:arc voltage (395 V/div), B:arc current (500 A/div), C:arc power (0.5 MW/div), D:arc energy (200 J/div), E,G:chamber pressure (5 bar/div), and F:barrel pressure 290 mm from arc chamber (5 bar/div). Sweep: A-F (200 μ s/div), G (1 ms/div)

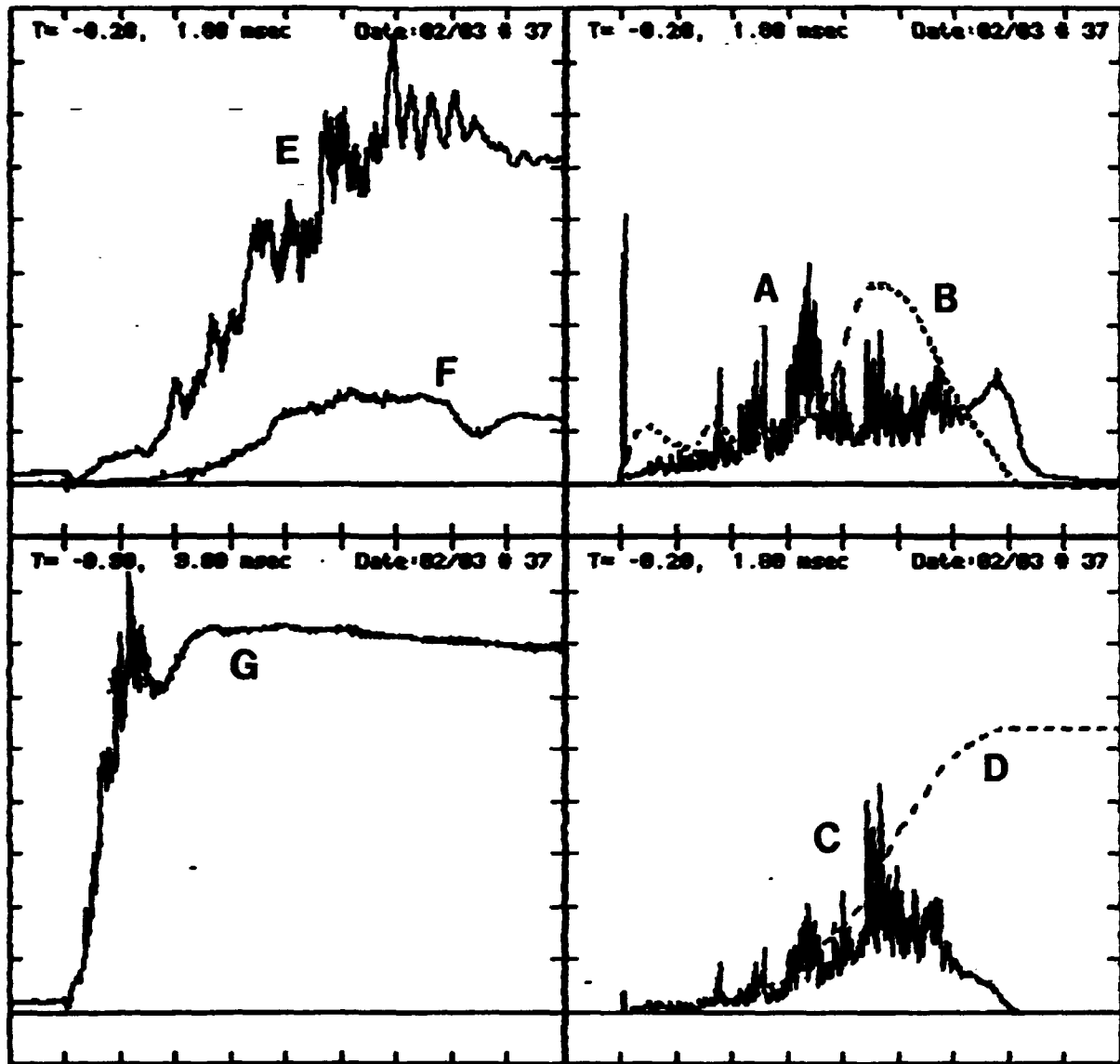


Fig.V.3: As Fig.V.2, but with 13 capacitors discharged.

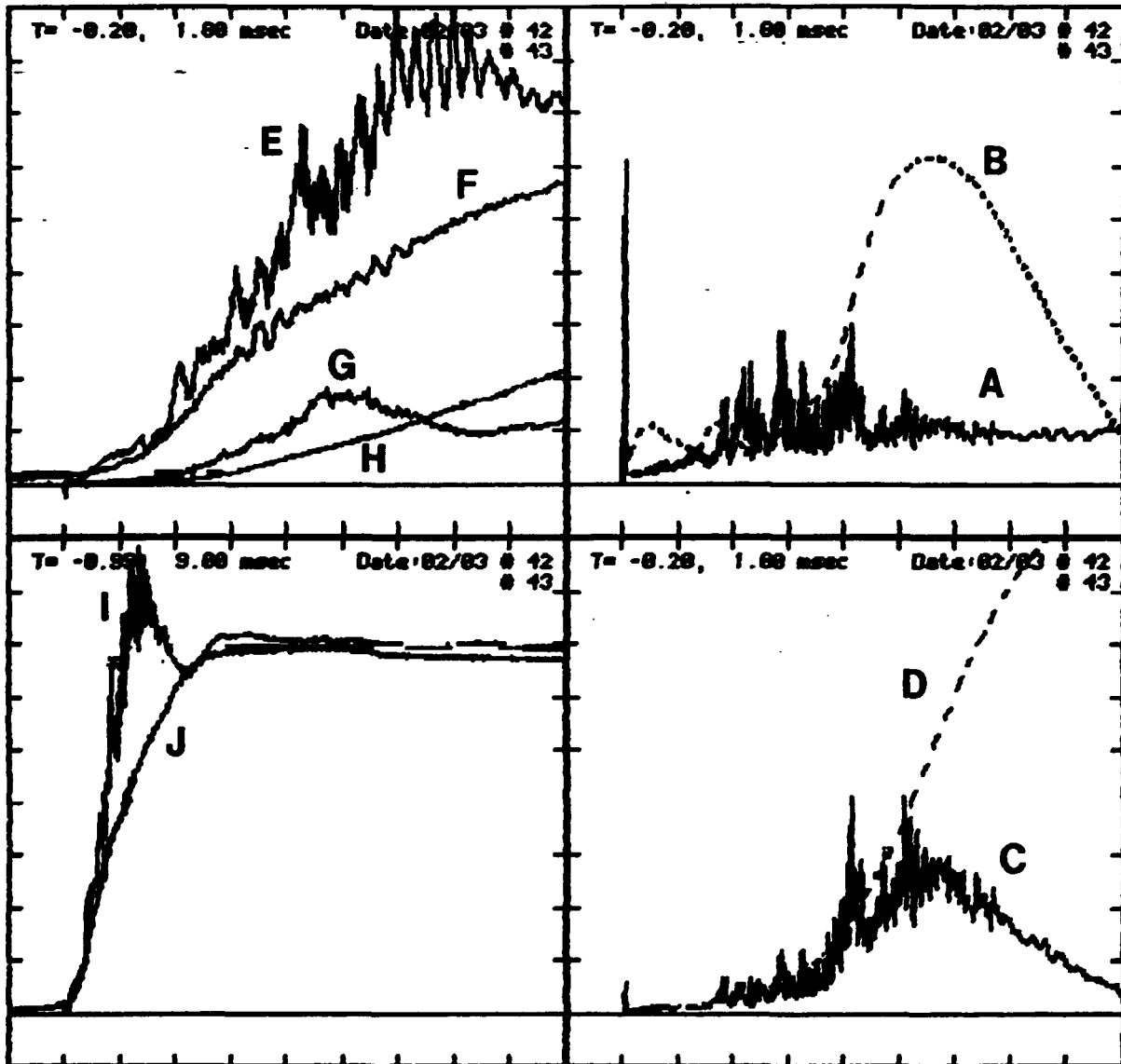


Fig.V.4: As Fig.V.2, but with 42 capacitors discharged.
A:arc voltage (395 V/div), B:arc current (500 A/div), C:arc power (0.5 MW/div), D:arc energy (200 J/div), E and I:chamber pressure with arc ignited (5 bar/div), F and J chamber pressure with out arc ignition (5 bar/div), G(with arc) and H(without arc):barrel pressure 290 mm from arc chamber (5 bar/div). Sweep: A-H (200 μs/div), I and J (1 ms/div)

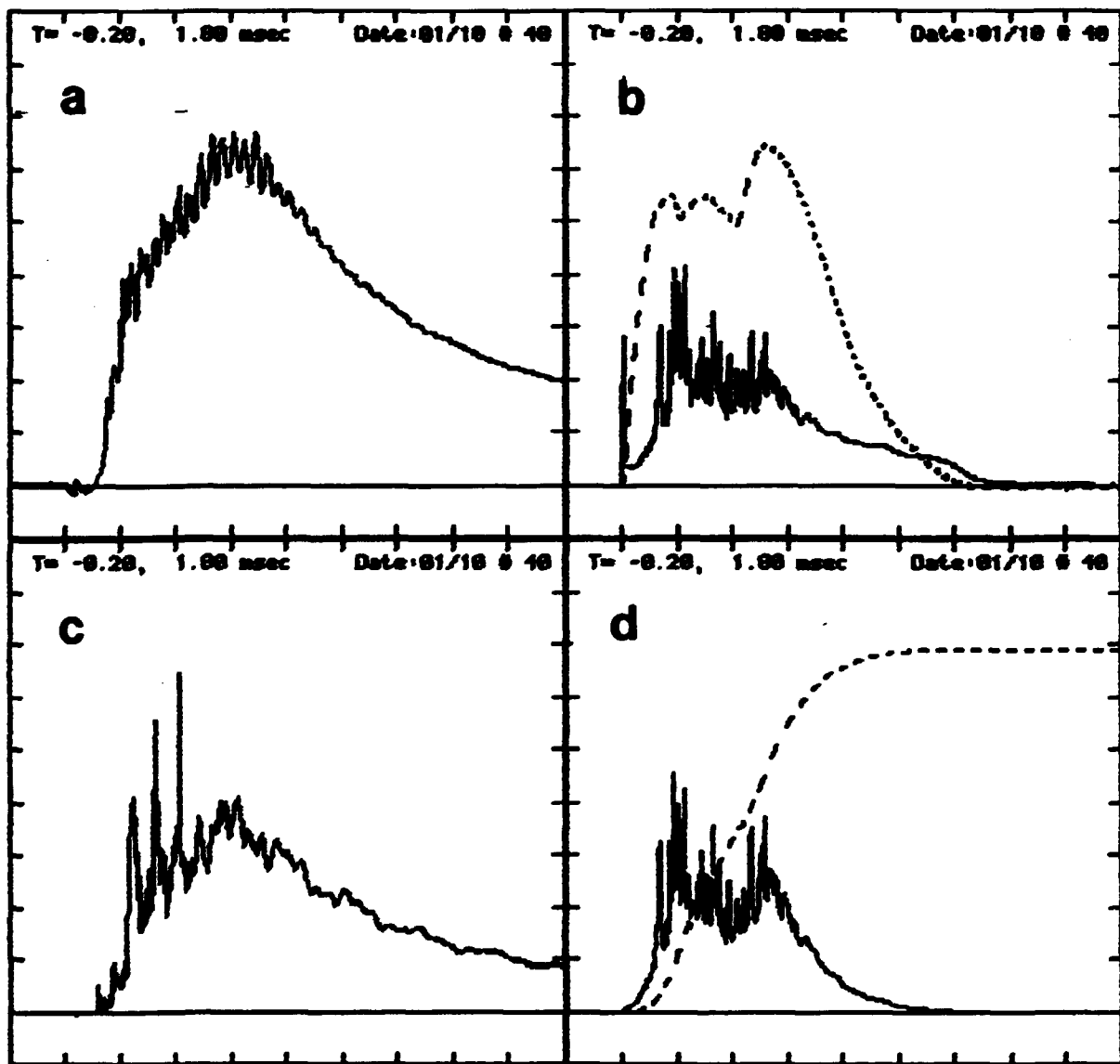


Fig.V.5: Arc characteristics and pressure transients. a:chamber pressure (25 bar/div), b:(solid line) arc voltage (390 V/div), b:(dashed line) arc current (500 A/div), c:barrel pressure (25 bar/div). d:(solid line) arc power (1MW/div), d:(dashed line) arc energy (200 J/div), sweep: (0.2 ms/div)

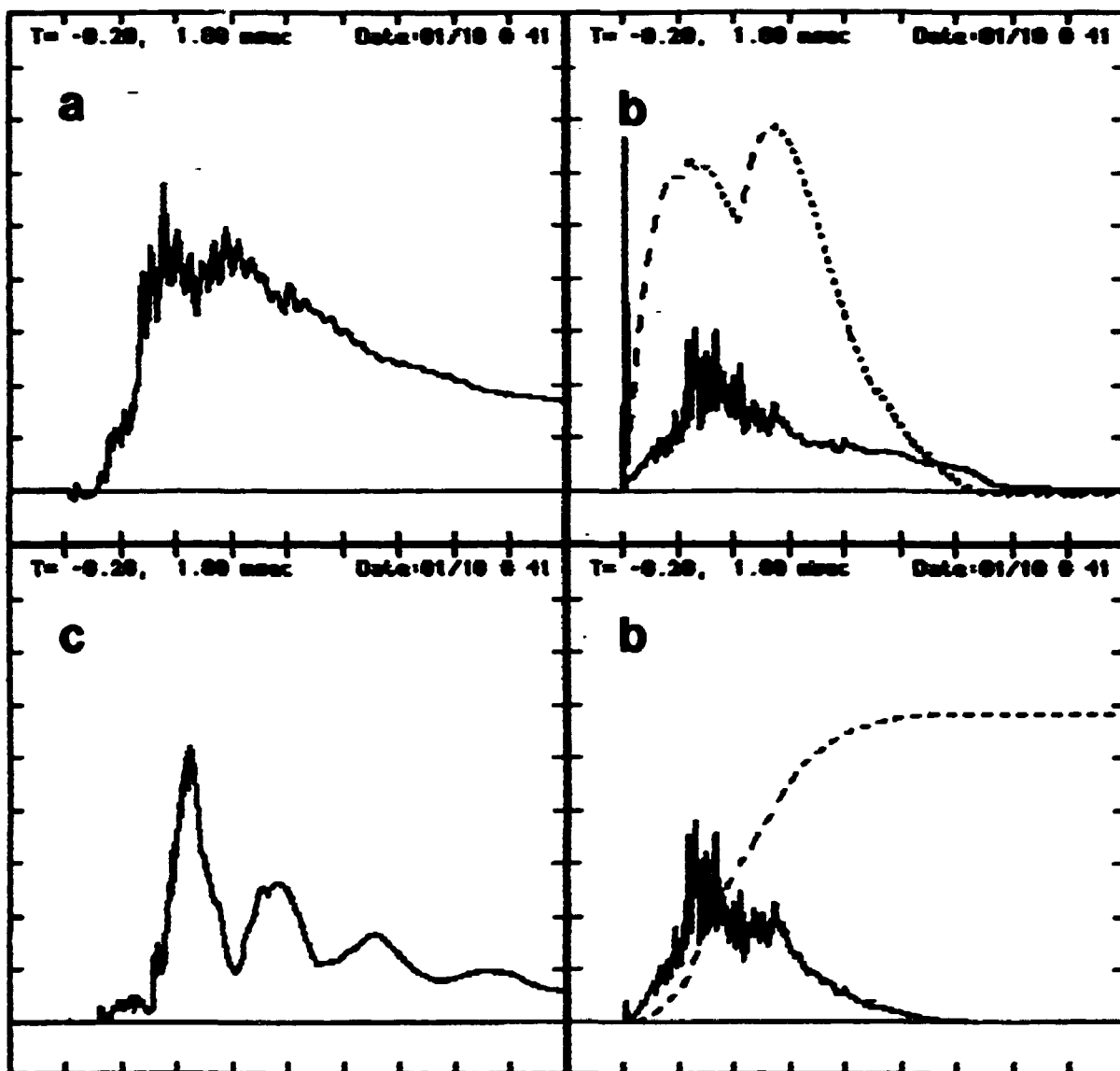


Fig.V.6: Shot with the same external conditions and the same scales as Fig.V.5

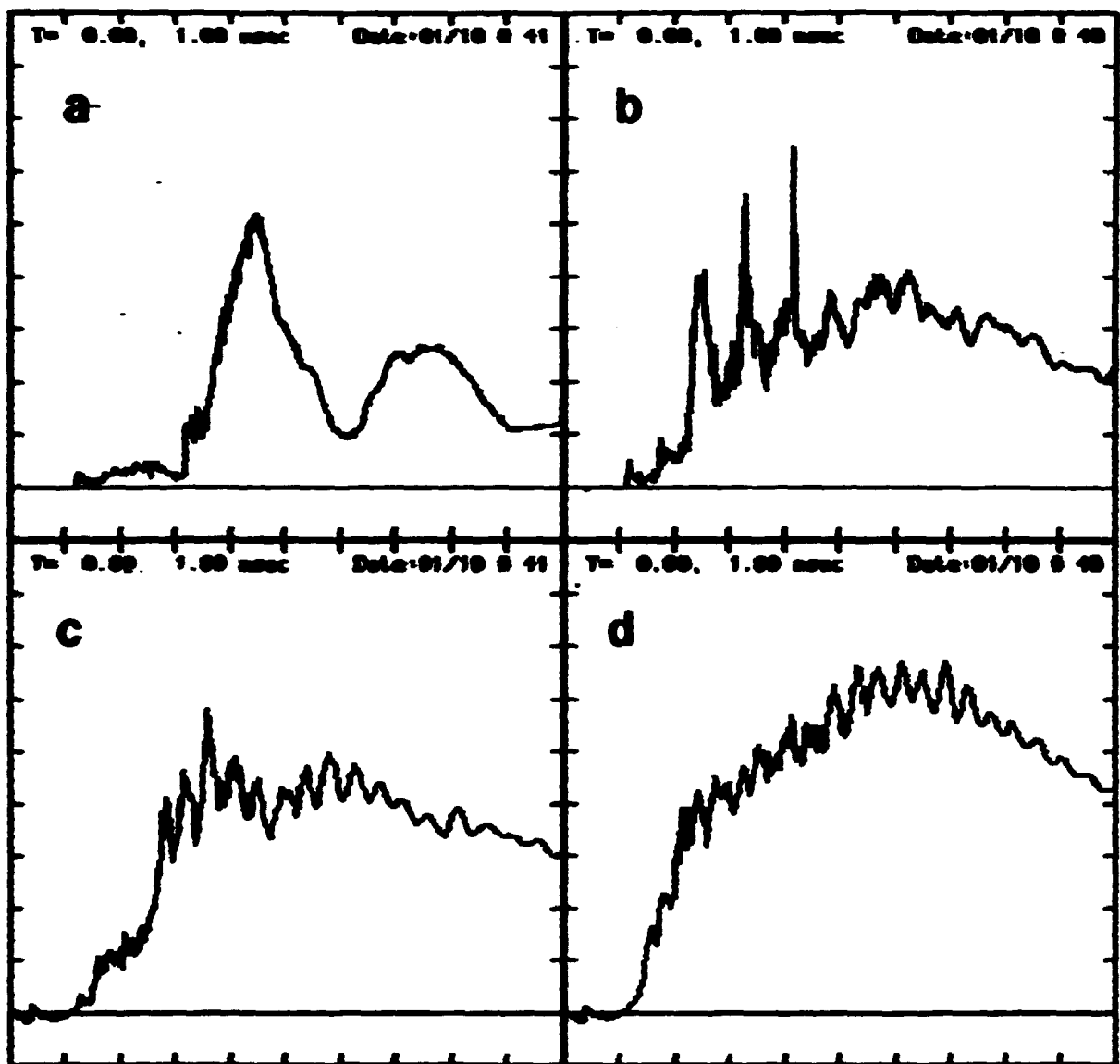


Fig.V.7: Comparison of oscillations in pressure of shot #40 and #41 from Fig.V.5 and Fig.V.6. a and b:barrel pressure (25 bar/div), c and d:chamber pressure (25 bar/div), sweep: (0.1 ms/div)

Set-up for fast propellant
pellet injection

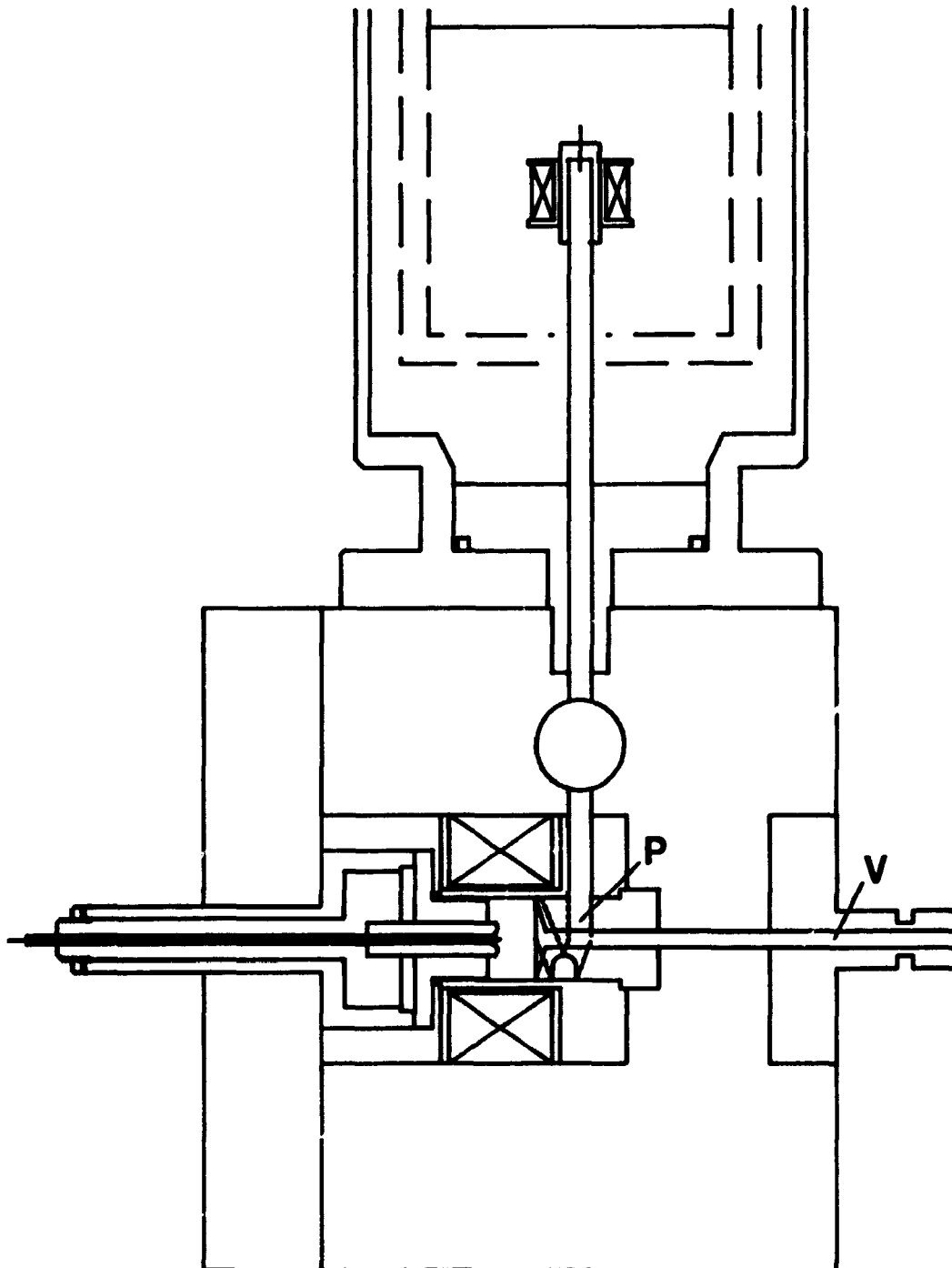


Fig.V.8: Set-up for fast propellant pellet injection

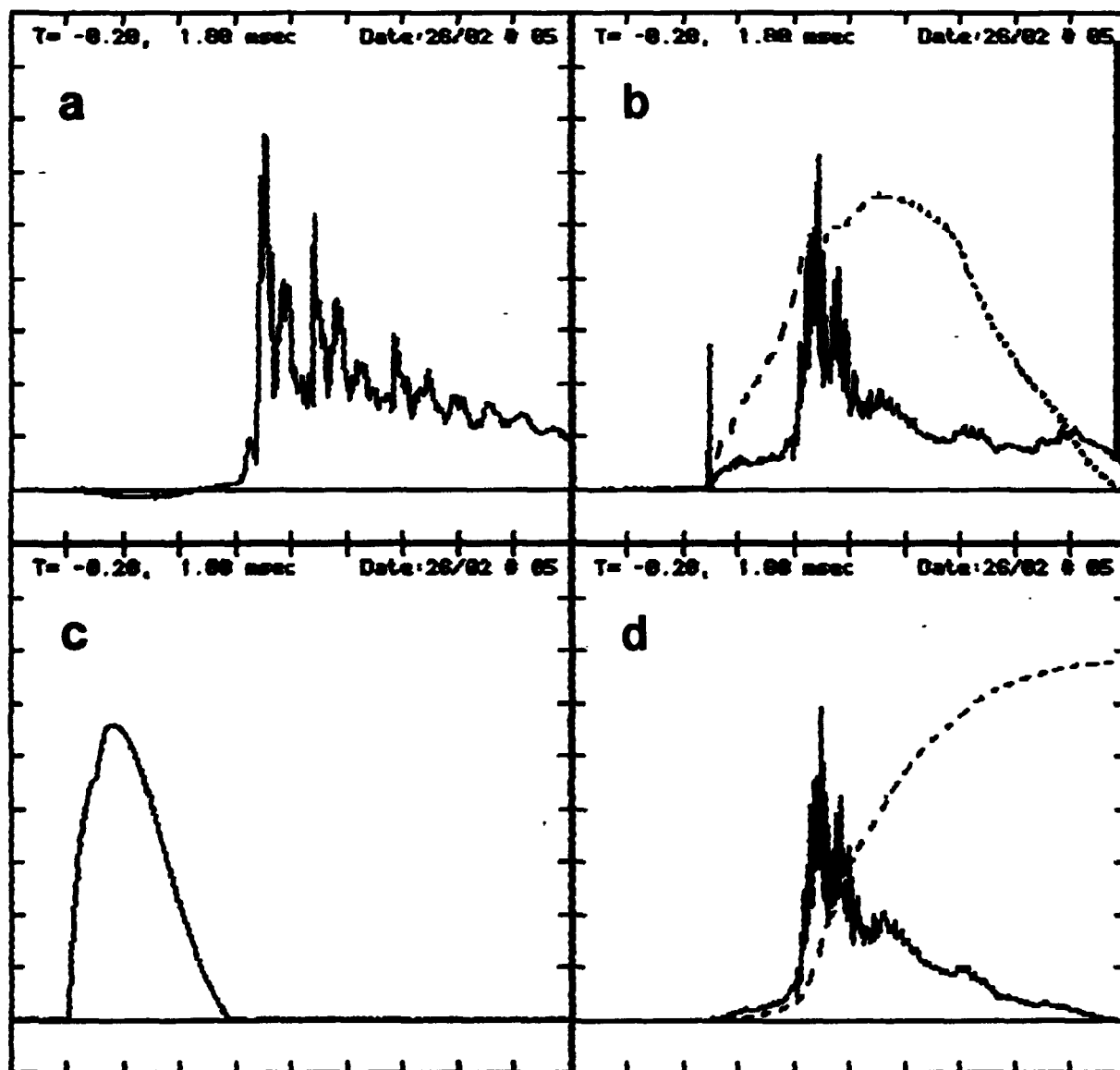


Fig.V.9: Shot with fast propellant pellet injection. a:chamber pressure (25 bar/div), b:(solid line) arc voltage (394 V/div), b:(dashed line) arc current (500 A/div), c:pipe gun arc current (200 A/div), and d:(solid line) power (1MW/div), (dashed line) energy (200 J/div), sweep (0.2 ms/div)

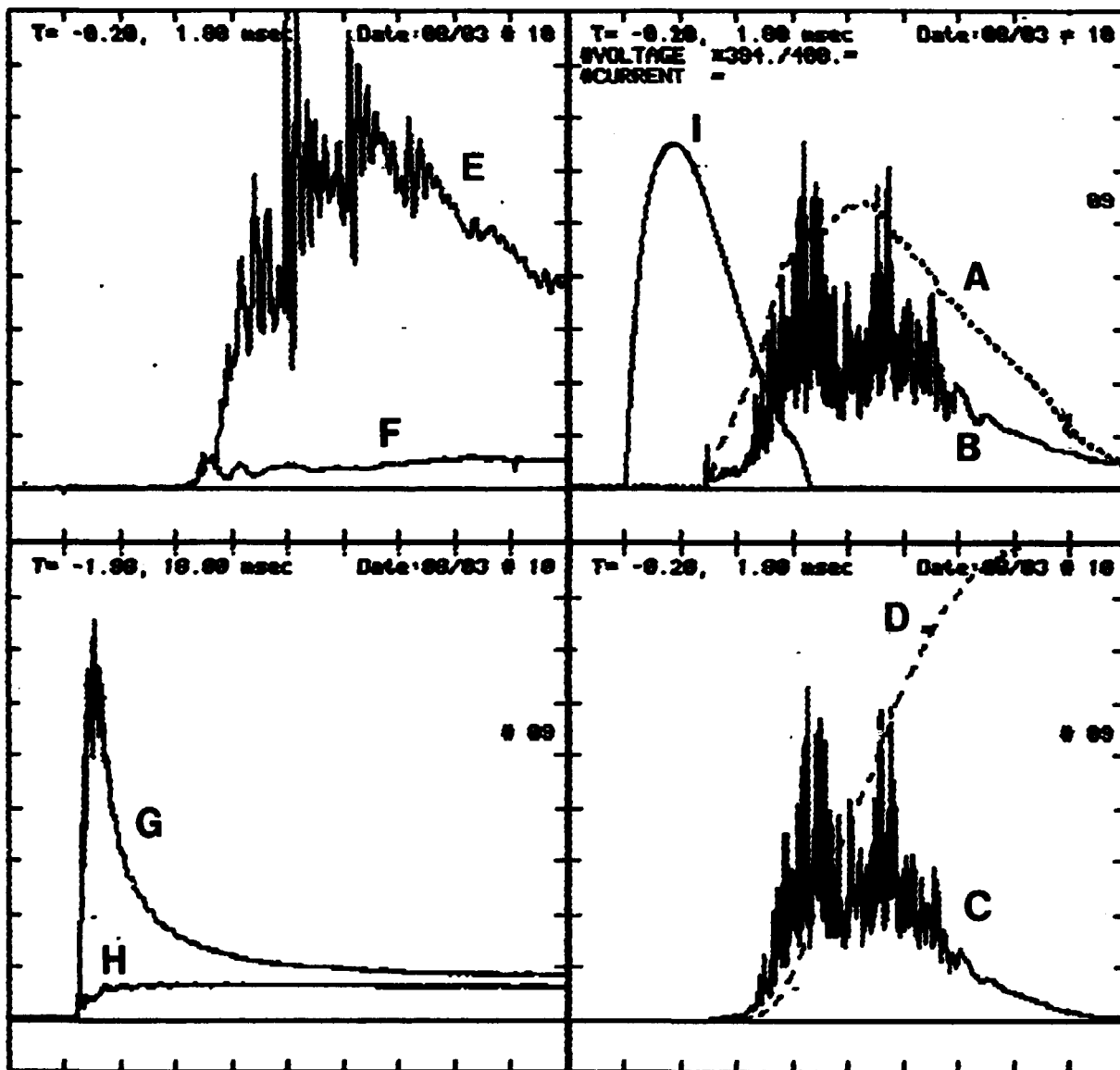


Fig.V.10: Data from two shots with arc (E,G) and without arc (F,H) and with closed arc chamber. A:arc current (500 A/div), B:arc voltage (395 V/div), C:arc power (0.5 MW/div), D:arc energy (200 J/div), E-G:chamber pressure (arc 25 bar/div), I:fast pipe gun arc current (200 A/div), sweep A-F (0.1 ms/div) and G-H (1 ms/div)

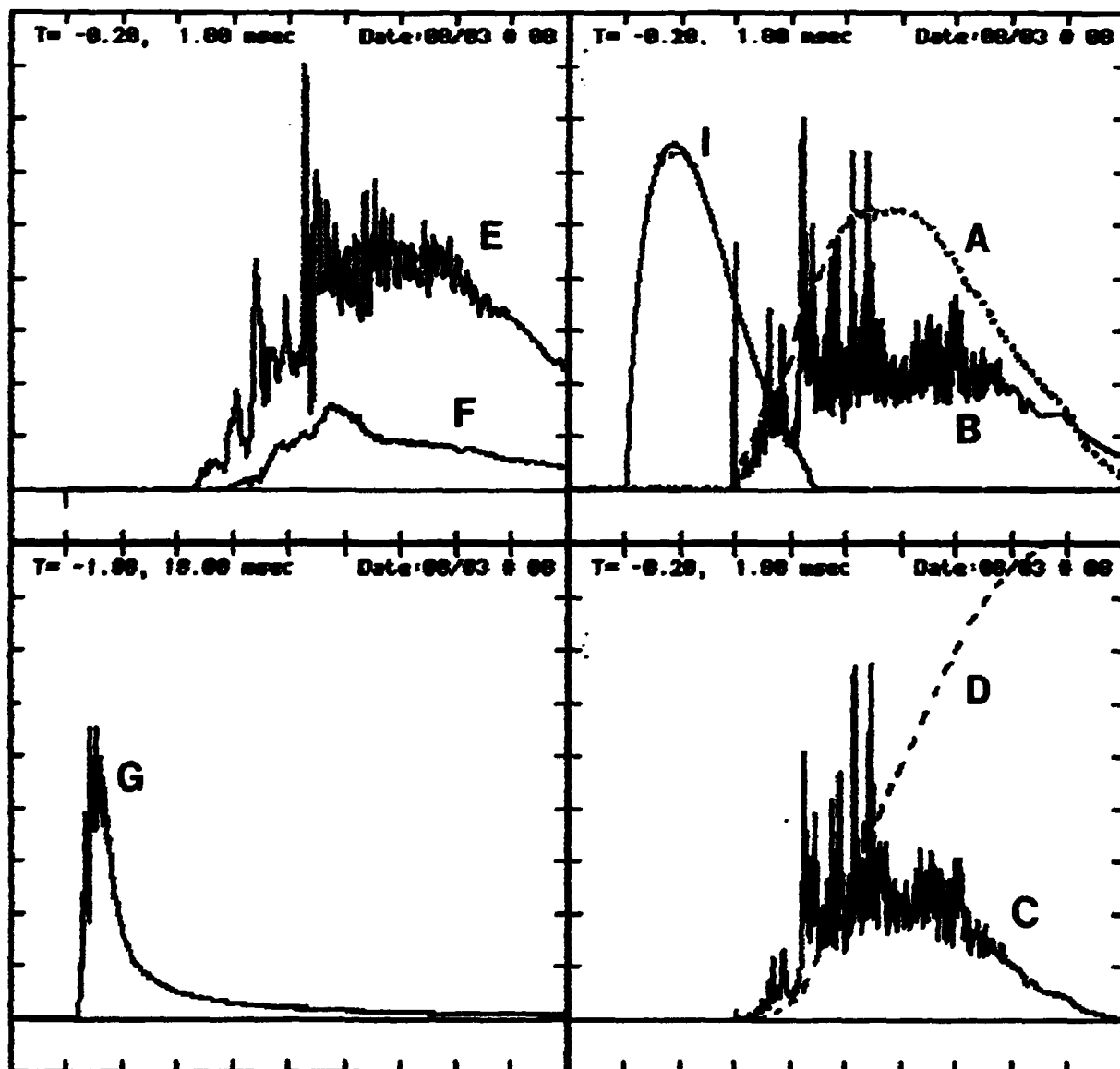


Fig.V.11: Data from shot with open barrel. A:arc current (500 A/div), B:arc voltage (395 V/div), C:arc power (0.5 MW/div), D:arc energy (200 J/div), E, G:chamber pressure (arc 25 bar/div), F:barrel pressure, 290 mm from arc chamber (25 bar/div), I:fast pipe gun arc current (200 A/div), sweep A-F (0.1 ms/div) and G (1 ms/div)

Title and author(s)		Date	December 1988
INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN*		Department or group	Physics
S.A. Andersen, L. Bækmark, V.O. Jensen. P. Michelsen, and K.V. Weisberg.		Groups own registration number(s)	
* This work was done under Art.-14 contract No. JR4/9006 Extension No 1 between the JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory.		Project/contract no.	
Pages	60	Tables	0
Illustrations	34	References	3
ISBN		87-550-1460-7	
Abstract (Max. 2000 char.)			
<p>Abstract. This report describes work on pellet acceleration by means of an arc heated gas gun. Preliminary results were described in Risø-M-2536 and in Risø-M-2650. This final report describes the work carried out from 1987.03.31 to 1988.09.30. An arc-heated hydrogen gas source, for pneumatic acceleration of deuterium pellets to velocities above 2 km/s, was developed. Experiments were performed with an arc chamber to which different methods of hydrogen supply were possible, and to which the input of electrical power could be programmed. Results in terms of pressure transients and acceleration curves are presented. Maximum pellet velocities approaching 2 km/s were obtained. This limit is discussed in relation to the presented data. Finally this report contains a summary and a conclusion for the entire project.</p>			
Descriptors - INIS			
<p>ACCELERATION; DEUTERIUM; PELLET INJECTION; PLASMA GUNS; PNEUMATIC TRANSPORT; TOKAMAK DEVICES; VELOCITY.</p>			
<p>Available on request from Risø Library, Risø National Laboratory, (Risø Bibliotek, Forskningscenter Risø), P.O. Box 48, DK-4000 Roskilde, Denmark. Telephone 02 37 12 12, ext. 2282. Telex: 43116, Telefax: 02 36 06 09</p>			

**Available on request from
Risø Library,
Risø National Laboratory,
P.O. Box 49, DK-4000 Roskilde, Denmark
Phone (02) 37 12 12 ext. 2262**

**ISBN 87-550-1460-7
ISSN 0418-6435**